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Genetic Analysis of Synaptotagmin C2 Domain Specificity in Regulating Spontaneous and Evoked Neurotransmitter Release

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Synaptic vesicle fusion mediates communication between neurons and is triggered by rapid influx of Ca$^{2+}$. The Ca$^{2+}$-triggering step for fusion is regulated by the synaptic vesicle transmembrane protein Synaptotagmin 1 (Syt1). Syt1 contains two cytoplasmic C2 domains, termed C2A and C2B, which coordinate Ca$^{2+}$ binding. Although C2A and C2B share similar topology, binding of Ca$^{2+}$ ions to the C2B domain has been suggested as the only critical trigger for evoked vesicle release. If and how C2A domain function is coordinated with C2B remain unclear. In this study, we generated a panel of Syt1 chimeric constructs in Drosophila to delineate the unique and shared functions of each C2 domain in regulation of synaptic vesicle fusion. Expression of Syt1 transgenes containing only individual C2 domains, or dual C2A-C2A or C2B-C2B chimeras, failed to restore Syt1 function in a syt1 null mutant background, indicating both C2A and C2B are specifically required to support fast synchronous release. Mutations that disrupted Ca$^{2+}$ binding to both C2 domains failed to rescue evoked release, but supported synaptic vesicle docking and endocytosis, indicating that these functions of Syt1 are Ca$^{2+}$-independent. The dual C2 domain Ca$^{2+}$-binding mutant also enhanced spontaneous fusion while dramatically increasing evoked release when coexpressed with native Syt1. Together, these data indicate that synaptic transmission can be regulated by Syt1 multimerization and that both C2 domains of Syt1 are uniquely required for modulating Ca$^{2+}$-independent spontaneous fusion and Ca$^{2+}$-dependent synchronous release.

Introduction

Neurotransmitter release at synapses occurs within milliseconds following Ca$^{2+}$ influx through voltage-gated channels (Linás et al., 1981; Neher and Zucker, 1993; Sabatini and Regehr, 1996; Sun and Wu, 2001; Wojcik and Brose, 2007). Although the full complement of Ca$^{2+}$ binding proteins that coordinate synaptic vesicle fusion is unknown, the synaptic vesicle protein Synaptotagmin 1 (Syt1) has emerged as a key Ca$^{2+}$ sensor that regulates fast synchronous release. Syt1 consists of a short intraluminal N-terminal region, a single transmembrane domain, and two cytoplasmic PKC-homologous repeats (C2 domains) that bind Ca$^{2+}$ via negatively charged aspartate residues (Perin et al., 1990; Perin et al., 1991; Sutton et al., 1995; Ubach et al., 1998; Desai et al., 2000). In vitro studies have demonstrated Ca$^{2+}$-dependent interactions between Syt1 and plasma membrane phospholipids (Brose et al., 1992; Chapman and Jahn, 1994; Sutton et al., 1995; Fernandez et al., 2001), as well as the neuronal SNARE complex (Chapman et al., 1995; Zhang et al., 2002). The loss of Syt1 severely impairs Ca$^{2+}$-dependent synchronous vesicle release (Geppert et al., 1994; Geppert et al., 1997; Voets et al., 2001; Yoshihara and Littleton, 2002; Nishiki and Augustine, 2004b; Liu et al., 2009).

To determine how Syt1 regulates fusion, several studies have focused on the function of its two C2 domains, termed C2A and C2B. Despite the robust interaction between the C2A domain and membrane phospholipids (Chapman and Davis, 1998; Bai et al., 2000; Bai et al., 2002; Stevens and Sullivan, 2003; Paddock et al., 2008), neutralization of negatively charged aspartate residues (D to N) in C2A does not disrupt synchronous neurotransmitter release (Fernández-Chacón et al., 2002; Robinson et al., 2002; Stevens and Sullivan, 2003). In contrast, a D229E substitution in the Drosophila C2A domain reduced vesicle fusion (Striegel et al., 2012), whereas neutralization of D232 (D232N) in mice enhanced synaptic transmission (Fernández-Chacón et al., 2002; Stevens and Sullivan, 2003; Pang et al., 2006a). Together, these results suggest that the C2A domain may regulate exocytosis, but its specific function remains unclear. In contrast to C2A, Ca$^{2+}$ binding to the C2B domain is required for synchronous release (Littleton et al., 1994; Littleton et al., 2001; Mackler et al., 2002; Nishiki and Augustine, 2004; Shin et al., 2009; Yoshihara et al., 2010).

Although these studies emphasize the importance of Ca$^{2+}$-binding to C2B, there is no experimental evidence to indicate that
C2B can function without C2A. Indeed, membrane penetration by Syt1 requires cooperativity between its tandem C2 domains (Bai et al., 2002; Herrick et al., 2006). Here, we tested the function of each C2 domain and identified cooperative actions of C2A and C2B that regulate release at Drosophila neuromuscular junctions (NMJs). We generated transgenic Syt1 constructs bearing Ca2+−binding mutations in each C2 domain or that expressed proteins with chimeric C2 domain structure. Our results indicate that the essential function for the C2B domain in fusion requires C2A. In addition, similar interactions are required for regulation of spontaneous vesicle release, suggesting that Syt1 C2 domain cooperativity regulates multiple synaptic vesicle release pathways.

Materials and Methods
Drosophila stocks and genetics. Drosophila melanogaster were cultured on standard medium at 22°C. Female larvae and adult flies were used for analyses described below unless indicated. DNA constructs for UAS-syntaptotagmin 1 (syt1)C2B-D3/4N encoding Syt1D16N, D18N (C2A−C2B+) were obtained from N.E. Reist (Colorado State University, Fort Collins, CO). DNA for UAS-syt1C2A-D3/4N encoding Syt1D282N, D284N (C2A−C2B−) was generated using the QuikChange MultiSite-Directed Mutagenesis Kit (Stratagene) with the primer ctcggtgctggcatccattcctgaagctc. A similar strategy was used to generate UAS-syt1C2A-D3/4N-C2B-D3/4N (C2A+C2B−) encoding Syt1D282N, D284N, D186N, D184N. Isolated C2 domain constructs with or without D3/4N mutations (C2A, C2A+, C2B, and C2B+) were generated by PCR reactions with the following primer sets: cgGAATTCattgccccgaactaatgcg (5′-EcoRI) and gcgCTCGAGagcgttgagaggagggac (3′-XbaI) for C2A and C2A+; cgGATCCTgagcgttgagaggagggac (5′-XhoI) for C2B and C2B+; gcgCTCGAGcttttcctgtccgccctctccttc (3′-Gateway). In addition, constructs composed of two homologous C2 domains tagged with hemagglutinin (C2A-C2A and C2B-C2B) were generated by the Drosophila Gateway vector system with the following primer sets: cgGAATTCattgccccgaactaatgcg (5′-EcoRI), gaAGATCTttcctgctggccctccttc (3′-BglI for the first C2A), GAAGATCCAGGACGACAGACGACGCG (5′-BglI for the second C2A), tcctCTAAGGctgtgtgtgccttcctc (3′-Xbal for the second C2A), CACGctgctgcgcaactaatgcg (5′-Gateway), and tcctCTAAGGACTtctgccttc (3′-Gateway) for C2A-C2A; cgGAATTCattgccccgaactaatgcg (5′-EcoRI), GAAGATCCAGGACGACAGACGACGCG (5′-BglI for the first C2B), GAAGATCCAGGACGACAGACGACGCG (5′-BglI for the second C2B), tcctCTAAGGACTtctgccttc (3′-Xbal for the second C2B), CACGctgctgcgcaactaatgcg (5′-Gateway), and tcctCTAAGGACTtctgccttc (3′-Gateway) for C2B-C2B. Transgenic strains were generated using standard microinjection into ice in TS buffer supplemented with protease inhibitors (Complete Mini Protease Inhibitor Cocktail Tablets, Roche Applied Sciences). The homogenate was subsequently solubilized with 0.5% Triton X-100 for 30 min at 4°C. The resulting supernatant (after removing cell debris by centrifugation at 15,000 × g for 20 min) was used in binding assays. Protein concentration of head supernatants was measured with Pierce BCA reagents (Thermo Fisher Scientific). GST-fused Syt1 immobilized on glutathione-Sepharose beads was incubated with head supernatants or His6-tagged Syt1 at 4°C for 2 h in TS buffer containing either 2 mM EDTA or 1 (or 10) mM Ca2+. Equal fractions were then subjected to SDS-PAGE and immunoblotted. Polyclonal antiserum against GFP (1:2000; Invitrogen) and Syt1 (1:200) was used for detection of protein binding.

Electron microscopy. Wandering third instar larvae expressing Syt1 transgenic constructs in the wild-type or syt1Δ−/− mutant backgrounds were dissected, fixed, and processed as previously described (Rodal et al., 2011), and subjected to a poststaining step with uranyl acetate (2%; Electron Microscopy Sciences) for electron microscopy. Thin sections (50 nm) were imaged at 80 kV on an electron microscope (Tecnai G2 Spirit BioTWIN).

Western blot analysis. Western blots were performed using standard laboratory procedures. Nitrocellulose membranes were probed with mouse anti-Discs-Large (Dlg) (4F3, 1:2000) and rabbit anti-Syt1 antibodies (1:200). The 4F3 antibody was obtained from the Developmental Studies Hybridoma Bank (University of Iowa, Iowa City, IA). Secondary antibodies from Jackson ImmunoResearch Laboratories, used at a dilution of 1:250, were as follows: FITC-conjugated goat anti-mouse, and rhodamine red/FITC-conjugated goat anti-HRP. Visualization was performed with confocal microscopy (Axioplan 2; Carl Zeiss Microscopy) using PASCAL software (Carl Zeiss Microscopy).

Results
Generation of Syt1 transgenic constructs defective in Ca2+ binding
It has been well established that five conserved aspartate residues (termed D1-D5) form a Ca2+−binding pocket within each C2 domain (Fig. 1A, asterisks; Shao et al., 1996; Sutton et al., 1999; Fernandez et al., 2001). Neutralization of these residues leads to a
The C2B domain can function as the sole Ca\(^{2+}\) binding module in neurotransmitter release (Littleton et al., 2001; Fernández-Chacón et al., 2002; Mackler et al., 2002; Stevens and Sullivan, 2003). Although the C2B domain is critical for activating synchronous vesicle release (Littleton et al., 2001; Stevens and Sullivan, 2003), two of the five conserved aspartate residues in each C2 domain in Syt1 constructs used for the analysis is shown. Syt1 consists of a short intraluminal region (blue line), a single transmembrane domain (dark green box), an intracellular linker (red), two C2 domains (C2A, C2B, or both C2 domains). These mutations (indicated hereafter as C2A*, C2B*, or C2A*-C2B*) were introduced into Syt1 transgenic lines with similar expression levels by Western analysis (Fig. 2B) were chosen for comparison in subsequent experiments.

**Figure 1.** Syt1 transgenic constructs and sequence similarity. A, Amino acid sequences of human, mouse, and Drosophila Syt1 are compared. A single transmembrane domain and two C2 domains, C2A and C2B, are indicated as dark green, blue, and light green boxes, respectively. The five aspartate residues (D) involved in binding Ca\(^{2+}\) ions in each C2 domain are indicated with red asterisks. The third and fourth of these five aspartate residues were mutated to asparagines (N) to disrupt Ca\(^{2+}\) binding ability of each C2 domain (red boxes). B, The design of transgenic UAS-Syt1 constructs used for the analysis is shown. Syt1 consists of a short intraluminal region (blue line), a single transmembrane domain (dark green box), a cytoplasmic linker (red), and two C2 domains (C2A, blue; C2B, green) with a short linker between them, and a C-terminal tail. *C2 domains containing mutations (described in A) (red boxes).
Cooperativity between Syt1 C2 domains in synchronous neurotransmitter release

Rescue data indicate that the C2B domain is the major Ca\(^{2+}\)-binding module involved in regulation of synchronous fusion. However, these results do not exclude a contribution from the C2A domain in C2B-driven Ca\(^{2+}\)-dependent exocytosis. Given that mutations in the C2B domain (C2A-C2B\(^*\)) led to a complete failure to rescue, regardless of the presence of a wild-type or Ca\(^{2+}\)-binding defective C2A domain (Fig. 3, C2A-C2B and C2A*-C2B\(^*\)), it is possible that C2B functions as a major Ca\(^{2+}\)-binding module without a C2A domain present. To assay the function of each C2 domain separately, we created transgenic constructs that deleted the entire C2A or C2B domain. In addition, we created chimeric transgenic lines that expressed a dual C2A-C2A or C2B-C2B Syt1 protein where the corresponding endogenous C2 domain was replaced to generate a homologous C2 domain architecture (Fig. 1B, right). A construct lacking the entire C2B domain (C2A only) was properly localized at NMJs, albeit at a lower level, when detected with anti-Syt1 antibodies. However, the counterpart lacking the C2A domain (C2B only) was not recognized by immunocytochemistry (data not shown), possibly because of a lack of antigenicity to C2B epitopes with our anti-Syt1 antibodies. To circumvent this problem, the dual C2A-C2A and C2B-C2B constructs were tagged with hemagglutinin. These constructs were detected at NMJs at similar patterns to endogenous Syt1 when visualized with an anti-hemagglutinin antibody (data not shown).

We first examined whether a functional C2A domain in the absence of C2B could restore release in syt\(^{−/−}\). Syt1 transgenes expressing C2A in the absence of C2B failed to rescue fast synchronous release, even in high extracellular [Ca\(^{2+}\)] (1.0 mM, Fig. 4A, B, p < 0.001). A similar failure to rescue was also observed in the case of Syt1 transgenes expressing C2A that lacks Ca\(^{2+}\)-binding ability (C2A\(^*\), data not shown). To determine whether the inability of C2A to restore release was due to the lack of a C2B domain or simply due to the requirement for the dual C2 domain structure found in all synaptotagmin isoforms (Sudhof and Rizo, 1996), we examined transgenic strains that replaced the C2B domain with a second C2A to retain the characteristic twin C2 domain structure (Figs. 1B, right, 4A, C2A-C2A). We observed that C2A-C2A transgenic rescue lines had no ability to restore release, as the amplitude of eEJPs remained similar to that in syt\(^{−/−}\) and far below control levels (Fig. 4B, p < 0.001). These data indicate that the C2A domain alone, or as a dual C2A-C2A module, cannot support fast synchronous release.

We next assayed whether C2B alone was sufficient to support synchronous release when expressed in syt\(^{−/−}\) mutants. Constructs expressing a Syt1 construct lacking the C2A domain were not capable of restoring synchronous release, regardless of the Ca\(^{2+}\)-binding ability of C2B (Fig. 4A,B, p < 0.001; data not shown for C2B\(^*\)). We next examined whether a transgenic protein expressing dual C2B domains (C2B-C2B) was able to function in vesicle fusion. Synchronous release in syt\(^{−/−}\) larvae expressing this construct was similar to that observed in syt\(^{−/−}\) alone (Fig. 4A), indicating that C2B cannot function in the absence of C2A (Fig. 4B, p < 0.001). In summary, these data demonstrate that Ca\(^{2+}\)-dependent exocytosis mediated by the C2B domain requires the presence of C2A, indicating that the activity of both C2 domains is specifically required to regulate synchronous synaptic vesicle fusion.

C2A and C2B function cooperatively to regulate spontaneous neurotransmitter release

In addition to evoked neurotransmitter release, Syt1 has been shown to regulate spontaneous fusion, as evidenced by the elevated rates of spontaneous release in syt\(^{−/−}\) null mutants (Di-Antonio and Schwarz, 1994; Geppert et al., 1994; Littleton et al., 1994; Mackler et al., 2002; Yoshihara and Littleton, 2002; Pang et al., 2006b; Xu et al., 2009). However, the role of the C2A and C2B domains in regulation of spontaneous fusion has just begun to be explored (Xu et al., 2009) and remains poorly characterized. We
examined whether C2A and C2B regulate spontaneous release by measuring mEJP frequency and amplitude in syt1/H11002 larvae rescued with control and mutated transgenic Syt1 constructs (Fig. 5). Consistent with previous reports, syt1/H11002 mutants displayed a slight but significant increase in the frequency of spontaneous release (Fig. 5A, B, bottom, p < 0.05). Expression of the wild-type Syt1 transgene (C2A-C2B) in syt1/H11002 larvae restored spontaneous release to control levels (Fig. 5A, B, bottom). Syt1 transgenes containing neutralization of two aspartate residues (D3/4N) in C2A (C2A*-C2B) appeared to be more effective in clamping spontaneous release compared with those rescued with wild-type Syt1, although the effect did not reach statistical significance (Fig. 5B, bottom, p = 0.32). In contrast to C2A mutations, mEJP frequency appeared elevated in larvae expressing Ca2+-binding mutations in C2B (C2A-C2B*) (Fig. 5B, bottom, p = 0.14), comparable to syt1/H11002 (Fig. 5A, B, bottom), suggesting that spontaneous release may be differentially regulated by Ca2+-binding to the C2A and C2B domains.

To determine whether the ability of C2B to regulate spontaneous fusion requires wild-type C2A, we assayed Syt1 transgenes expressing Ca2+-binding mutants in both C2 domains (C2A*-C2B*). Surprisingly, expression of the C2A*-C2B* transgenic rescue in the syt1/H11002 null background induced a dramatic increase in mEJP frequency regardless of external [Ca2+] (Fig. 5A, B, bottom, p < 0.001). The elevated mini-frequency was far beyond the levels observed in syt1/H11002 mutants alone or rescue strains expressing C2A-C2B* (Fig. 5B, p < 0.001, C2A*-C2B* vs syt1/H11002 or C2A-C2B*).

The increase in spontaneous release induced by expression of a Ca2+-binding defective form of Syt1 could be secondary to
Ca\(^{2+}\)-independent roles for the protein in synaptic vesicle docking, priming, or endocytosis that enhance the number of docked synaptic vesicles. To test this possibility, we examined the distribution of synaptic vesicles in syt1\(^{-/-}\) null mutants expressing C2A*-C2B* using transmission electron microscopy and compared them with null mutants alone or rescue lines expressing the wild-type Syt1 protein (C2A-C2B). As previous reports have indicated (Reist et al., 1998; Liu et al., 2009; Young and Neher, 2009), syt1\(^{-/-}\) null mutants displayed a reduction in docked synaptic vesicles (Fig. 6A,D, black column, \(p < 0.001\)), as well as a reduced vesicle density, measured as the number of vesicles per unit bouton area (Fig. 6E, \(p < 0.001\)). Expression of C2A*-C2B* resulted in an increase in docked synaptic vesicles adjacent to active zones, similar to that in strains expressing the wild-type transgene (Fig. 6A,D, black columns). Likewise, vesicle density in syt1\(^{-/-}\) mutants expressing C2A*-C2B* was comparable to syt1\(^{-/-}\) animals rescued with the wild-type protein and significantly greater than animals lacking Syt1 altogether (Fig. 6E, \(p < 0.001\)). We conclude that a Syt1 transgene with no Ca\(^{2+}\)-binding ability (C2A*-C2B*) can partially rescue defects in synaptic vesicle docking and total vesicle number. Given that docked vesicle number is similar in syt1\(^{-/-}\) mutants expressing the wild-type or C2A*-C2B* Syt1, it is unlikely that structural changes in synaptic vesicle distribution underlie the enhanced spontaneous release induced by C2A*-C2B* (Fig. 5A,B). Rather, Ca\(^{2+}\)-binding defective Syt1 appears to increase the fusogenicity of synaptic vesicles, resulting in a dramatic elevation in mEJP frequency.

Because the effects on evoked release suggested cooperative actions of the C2 domains, we investigated whether such cooperativity between C2 domains exists for the regulation of spontaneous release. We tested the role of the C2 domains by measuring mEJP frequency and amplitude in syt1\(^{-/-}\) mutants expressing single or dual C2 domains in either wild-type or mutated form (C2A, C2A*, and C2A-C2A; C2B, C2B*, and C2B-C2B). mEJP frequency in larvae expressing transgenic constructs that lack C2B (C2A, C2A*, and C2A-C2A) remained comparable with syt1\(^{-/-}\) mutants (Fig. 5C,D, gray dashed line) but was still far below the level of those expressing C2A*-C2B* (Fig. 5D, black dashed line, \(p < 0.001\)). Similarly, transgenic constructs consisting solely of the C2B domain (C2B, C2B*, and C2B-C2B) failed to rescue the increased mini-frequency in null mutants (Fig. 5C,D) but remained far below the level observed in syt1\(^{-/-}\) rescued with C2A*-C2B* (Fig. 5D, \(p < 0.001\)). These results indicate that cooperativity between C2A and C2B is required not only for synchronous neurotransmitter release but also for Syt1 function as a partial clamp of spontaneous release. It should be noted that there are no observed Ca\(^{2+}\)-dependent changes in mEJP frequency within a range (0.2–2.0 mM) of external Ca\(^{2+}\) at Drosophila NMJs (data not shown), in contrast to the Ca\(^{2+}\)-dependent nature of spontaneous release at mammalian synapses (Xu et al., 2009; Kochubej and Schneggenburger, 2011). Thus, it is likely that Syt1 exerts its function as a partial clamp in a Ca\(^{2+}\)-independent manner. Given that C2A*-C2B* lacks Ca\(^{2+}\)-binding ability and Ca\(^{2+}\)-dependent interaction with SNAREs (Earles et al., 2001; Shin et al., 2009), the mutated protein may alter Ca\(^{2+}\)-independent interactions of Syt1 with other partners regulating vesicle release, such as SNAREs and membrane phospholipids. Unlike mEJP frequency, mEJP amplitude remained similar among the different transgenic expressions, except for syt1\(^{-/-}\) larvae expressing a C2B-C2B chimeric protein, which significantly enhanced mEJP amplitude (Figs. 5C, 6B, \(p < 0.001\)). The increase in mEJP amplitude in C2B-C2B–expressing animals was associated with the appearance of significantly larger synaptic vesicles by transmission electron microscopy (Fig. 6A, arrowheads) and with an increase in diameter of synaptic vesicles near active zones, compared with syt1\(^{-/-}\) rescued with the wild-type Syt1 (C2A-C2B) (Fig. 6C). Furthermore, we also found a significant reduction in the number of vesicles distant from active zones in syt1\(^{-/-}\) larvae expressing a C2B-C2B protein (Fig. 6D), resulting in a reduced total vesicle density similar to syt1\(^{-/-}\) (Fig. 6E, \(p < 0.001\)). The Syt1 C2B domain is known to interact with several proteins involved in synaptic vesicle endocytosis (Jorgensen et al., 1995; Hauke and De Camilli, 1999; Littleton et al., 2001; Poskanzer et al., 2003; Nicholson-Tomishima and Ryan, 2004; Yao et al., 2012a; Yao et al., 2012b). Considering that the distribution of vesicles near active zones in syt1\(^{-/-}\) rescued with C2B-C2B was restored to wild-type levels (Fig. 6D, black column), our findings argue that the C2B-C2B protein is capable of promoting vesicle docking similar to wild-type Syt1. In contrast, the reduction in total vesicle density, together with the increased vesicle diameter and enlarged mEJP amplitude, indicates that the
dual C2B-C2B protein likely alters the association of Syt1 with the endocytotic machinery, resulting in defects in vesicle number and size.

Enhanced neurotransmitter release induced by coexpression of native and Ca\(^{2+}\)-insensitive Syt1

Although expression of transgenic constructs in the syt1\(^{-/-}\) null background allows characterization of their function in the absence of endogenous Syt1, overexpression of these constructs in the wild-type background can assay any dominant-negative or gain-of-function properties of the mutant proteins. Prior work demonstrated that overexpression of the Ca\(^{2+}\)-binding C2B mutant (C2A-C2B\(^*\)) induces a decrease in evoked neurotransmitter release at Drosophila larval NMJs (Mackler et al., 2002). We observed a similar effect caused by overexpression of C2A-C2B\(^*\) using elav\(^{c155}\)-GAL4, which resulted in a significant decrease in eEJP amplitude compared with overexpression of wild-type Syt1 (C2A-C2B) (Fig. 7A, \(p < 0.001\)). Such dominant-negative effects on synchronous release were accompanied by an increase in asynchronous release (Fig. 7A, arrows) and enhanced spontaneous fusion (Fig. 7B, bottom), presumably because of the altered nature of the mutated Syt1 C2B domain interaction with membrane phospholipids (Paddock et al., 2011).

Whereas overexpression of wild-type or C2A Ca\(^{2+}\)-binding Syt1 mutants (C2A*-C2B) did not alter EJP amplitude at 0.2 mM extracellular [Ca\(^{2+}\)], overexpression of the C2A*-C2B\(^*\) protein that completely lacks Ca\(^{2+}\)-binding ability induced a dramatic increase in EJP amplitude (Fig. 7A, \(p < 0.001\)) without affecting asynchronous release or spontaneous fusion (Fig. 7B). Such enhancement in synchronous release could reflect an increase in the number of synaptic vesicles available for immediate release. To test this hypothesis, we examined the synaptic ultrastructure of larvae expressing wild-type or C2A*-C2B\(^*\) Syt1 (Fig. 8A, B). We found no discernible abnormalities associated with overexpression of C2A*-C2B\(^*\), including no significant increase in the number of synaptic vesicles near active zones (Fig. 8B). Indeed, the
total number of synaptic vesicles residing within a 200 nm radius of active zones was mildly reduced in larvae overexpressing C2\textsuperscript{A*-C2B*} compared with wild-type Syt1 (Fig. 8B, \( p = 0.10 \)), suggesting that the enhanced synchronous release is not secondary to increases in docked vesicles. Another possibility for the enhanced evoked release induced by C2\textsuperscript{A*-C2B*} would be an increase in the number of release sites. However, there was no significant change in the number of release sites when visualized by immunoreactivity against the active zone protein Bruchpilot (Fig. 8C,D), indicating that structural changes are unlikely to contribute to the increased synchronous release upon overexpression of C2\textsuperscript{A*-C2B*}.

We next investigated which functional aspects of the release process were modified by overexpression of C2\textsuperscript{A*-C2B*}. For in-
Ca\textsuperscript{2+} conditions to support synchronous release. Furthermore, the paired-pulse ratio was significantly reduced in C2A*-C2B*-overexpressing larvae compared with animals overexpressing wild-type Syt1 (Fig. 7D). Given that the paired-pulse ratio reflects release probability during the first stimulation, these results indicate that overexpression of C2A*-C2B* enhances synchronous release by increasing release probability and lowering the [Ca\textsuperscript{2+}] \textsuperscript{tot} required to trigger fusion.

**Multimerization of native and Ca\textsuperscript{2+}-binding defective Syt1**

Our results demonstrate that expression of a Ca\textsuperscript{2+}-binding defective Syt1 (C2A*-C2B*) protein in the absence of native Syt1 robustly increases the rate of spontaneous fusion (Fig. 5), without restoring fast synchronous release (Fig. 3). In contrast, coexpression of C2A*-C2B* and native Syt1 resulted in a large enhancement in synchronous release (Fig. 7A), with no increase in spontaneous fusion (Fig. 7B).

If Syt1 regulates synaptic release as a monomer, we predicted that a mixed population of Ca\textsuperscript{2+}-binding defective and native Syt1 monomers would yield one of several possibilities: (1) both synchronous and spontaneous release would remain unchanged compared with control if native wild-type monomers in a mixed population are sufficient to perform the full repertoire of Syt1 functions; (2) synchronous release would be partially disrupted with a slight elevation of spontaneous release if wild-type and Ca\textsuperscript{2+}-binding defective Syt1 monomers participate independently in regulating both synchronous and spontaneous release; or (3) synchronous and spontaneous release will be differentially disrupted if native and mutated Syt1 monomers contribute unequally to different modes of synaptic release, resulting in either relatively normal synchronous release with a slightly enhanced spontaneous release or impaired synchronous release with a wild-type level of spontaneous fusion. However, our results are not consistent with these predictions, given the normal rate of spontaneous release with enhanced synchronous fusion caused by coexpression of Ca\textsuperscript{2+}-binding defective and native Syt1 (Fig. 7A, B). These results suggest the possibility of a Syt1 hetero-multimeric complex where native Syt1 clamps spontaneous release, whereas C2A*-C2B* Syt1 promotes evoked fusion. Indeed, the synaptic release with a wild-type level of spontaneous release is partially disrupted in larvae overexpressing wild-type Syt1 (C2A*-C2B*) and native Syt1 constructs. Given the normal rate of spontaneous release, our results are not consistent with predictions regarding the possibility of a Syt1 hetero-multimeric complex.

**Figure 7.** Interplay between endogenous and transgenic Syt1 constructs on evoked synchronous release. A, Top, Representative traces of two consecutive eEJPs recorded in the presence of low [Ca\textsuperscript{2+}] \textsuperscript{tot} (0.2 mM) are shown for wild-type larvae overexpressing the indicated transgenic Syt1 constructs. Calibration: 5 mV, 200 ms. Asynchronous release events during stimulation are indicated with arrows. Bottom, Mean eEJP amplitude is summarized for the indicated genotypes. Animals carrying each transgenic structure without a GAL4-driver (white) served as controls for comparison with the same transgenic constructs driven by elav\textsuperscript{C155-GAL4} (gray). B, Mean eEJP amplitude (top) and frequency (bottom) are summarized for the indicated genotypes. A, B, Number of NMJs examined (control and transgene expression): C2A-C2B, 7 and 8; C2A*-C2B, 5 and 8; C2A-C2B*, 11 and 8; and C2A*-C2B*, 10 and 11. C, Log-log plot for eEJP amplitudes at varying [Ca\textsuperscript{2+}] \textsuperscript{tot} is shown for animals overexpressing the C2A*-C2B* construct (gray) and its transgenic control without a GAL4-driver (black). The slope values calculated from a linear fit of the first three data points (0.075–0.2 mM [Ca\textsuperscript{2+}] \textsuperscript{tot}) are indicated in the box. Number of NMJs examined (control and transgene expression): 7 and 11 at 0.075 mM, 7 and 11 at 0.15 mM; 6 and 11 at 0.2 mM; 6 and 10 at 0.3 mM; and 6 and 9 at 0.5 mM. D, The ratios of eEJP responses in a paired-pulse stimulation paradigm are displayed for wild-type animals overexpressing the C2A-C2B (white) or C2A*-C2B* (gray) constructs. Number of NMJs examined (C2A-C2B and C2A*-C2B*): 8 and 6 at 30 ms interval; 8 and 7 at 50 ms; and 8 and 7 at 100 ms. A–D, Data are mean ± SEM. ***p < 0.001, **p < 0.01, and *p < 0.05. Student’s t test for control (UAS-transgene) versus neuronal expression (C155-GAL4, UAS-transgene) (A–C) or for neuronal overexpression of C2A-C2B versus C2A*-C2B* (D).
which might underlie the enhanced synchronous release observed in larvae overexpressing C2A*-C2B*.

We purified GFP-tagged full-length Syt1 expressed in syt1/H11002 fly heads and performed pull-down assays with GST-fused wild-type (GST-C2A-C2B) or mutated (GST-C2A*-C2B*) recombinant Syt1 (Fig. 9A). Purified GFP-tagged Syt1 bound to the cytoplasmic C2 domains of Syt1 immobilized on glutathione-Sepharose beads in the absence of Ca2+/H11001, as visualized by GFP immunoreactivity (Fig. 9A, EGTA, 2 mM). Further multimerization of Syt1 was observed by increasing [Ca2+] to 1 or 10 mM (Fig. 9A). These Ca2+-independent and Ca2+-dependent interactions did not differ between wild-type and C2A*-C2B* Syt1 (Fig. 9A). Similar results were obtained when we performed pull-down assays with His-tagged wild-type cytoplasmic Syt1 C2 domains to bind GST-fused wild-type or mutated recombinant Syt1. Ca2+-independent binding between His-Syt1 and GST-fused Syt1 (wild-type and C2A*-C2B*) was consistently detected (Fig. 9B). As seen with endogenous Syt1 pull-down, the interaction between His-Syt1 and GST-tagged Syt1 was enhanced in response to Ca2+ (Fig. 9B). Together, these findings indicate that endogenous Syt1 and Ca2+-binding defective Syt1 likely form hetero-multimers in the absence of Ca2+, which enhances the fusogenicity of synaptic vesicles in response to Ca2+ (Fig. 7).

**Discussion**

**Requirement of tandem Syt1 C2A-C2B domains in regulation of neurotransmitter release**

Using transgenic rescue approaches with chimeric Syt1 proteins, we demonstrate that both the C2A and C2B domains are individually required for Syt1 function in regulating vesicle release at the Drosophila NMJ. Prior studies have established that the C2B domain of Syt1 is a critical module for activating synchronous vesicle release in Drosophila (Littleton et al., 1994; Littleton et al., 2001; Mackler et al., 2002; Yoshihara et al., 2010). In contrast, the
contribution of the C2A domain is still being elucidated (Yoshihara et al., 2010; Striegel et al., 2012). Although the activities of isolated C2 domains in their interaction with SNAREs and membrane phospholipids remain controversial in in vitro studies, growing evidence suggests synergistic actions of both C2 domains. Isolated C2 domains, either C2A or C2B, bind syntaxin and SNAP-25 less effectively than C2A-C2B constructs in response to Ca\(^{2+}\) in in vitro binding assays (Chapman et al., 1996; Rickman and Davletov, 2003) or reconstituted vesicle fusion assays (Tucker et al., 2004). Synergistic actions of the C2 domains also occur during lipid binding, as isolated C2 domains bind poorly to liposomes made from chromaffin granule lipid extracts compared with dual C2A-C2B proteins (Damer and Creutz, 1994). Likewise, the interaction between the C2B domain and membrane phospholipids requires an intact C2A domain, even in the absence of its Ca\(^{2+}\)- and lipid-binding abilities (Bai et al., 2002). Furthermore, Ca\(^{2+}\)-dependent penetration of both C2 domains into reconstituted lipid bilayers appears to occur simultaneously (Hui et al., 2006). These in vitro studies indicate that cooperative actions of C2 domains regulate SNARE and lipid interactions and match our in vivo observations that evoked neurotransmitter release requires both C2 domains of Syt1.

In addition to a dual C2 domain structure, our findings indicate that C2A and C2B are uniquely required. Double C2 domain constructs containing only C2A-C2A fail to restore Syt1 function (Fig. 4), consistent with a lack of Ca\(^{2+}\)-dependent binding to t-SNAREs in the absence of C2B (Earles et al., 2001). Similarly, Syt2 constructs lacking the C2B domain at the calyx of Held failed to support evoked fusion in the null mutant background (Kochubey and Schneggenburger, 2011). Although the C2B domain rather than C2A plays a more prominent role in evoked fusion (Fig. 3), our results also indicate that the C2B domain is not solely responsible for Syt1 function in synaptic vesicle fusion, as an isolated or dual C2B domain cannot support synaptic vesicle fusion (Fig. 4). In addition, dual C2B-C2B constructs induce additional defects in vesicle endocytosis pathways that increase vesicle size and mEJP amplitude (Fig. 6). This contrasts with the ability of purified Syt1 dual C2B domains to induce liposome aggregation and SNARE-dependent vesicle fusion comparable with the wild-type Syt1 (C2A-C2B) in vitro (Hui et al., 2011), indicating a limitation of in vitro fusion assays in recapitulating in vivo requirements for synaptic vesicle release.

### Regulation of spontaneous fusion by Syt1 C2 domains

In addition to triggering synchronous fusion, Syt1 also partially clamps spontaneous fusion in the absence of a Ca\(^{2+}\) signal. Transgenic constructs with Ca\(^{2+}\) binding mutations in C2A fully rescued the elevated spontaneous fusion rate in syt1\(^{-/-}\) null mutants, whereas those with Ca\(^{2+}\) binding mutations in C2B did not (Fig. 5). Prior in vitro studies have demonstrated that C2A*-C2B is indistinguishable from wild-type C2A-C2B in its binding to membrane phospholipids (Bai et al., 2002; Bai et al., 2004), whereas mutations in the C2B domain (C2A-C2B\(^{*}\)) facilitated Ca\(^{2+}\)-independent binding of Syt1 to phospholipids (Mackler et al., 2002). Such differences in Ca\(^{2+}\)-independent lipid binding may underlie the differential regulation of spontaneous release in syt1\(^{-/-}\) mutants rescued with C2A*-C2B versus C2A-C2B\(^{*}\). Alternatively, neutralizations of these Ca\(^{2+}\)-binding residues may induce differential changes in C2 domain structure that influence Ca\(^{2+}\)-independent interactions between Syt1 and SNAREs. Syt1 has been shown to form a Ca\(^{2+}\)-independent complex with SNARE proteins in vitro (Bennett et al., 1992; Rickman and Davletov, 2003; Shin et al., 2003) and to stabilize partially assembled trans-SNARE complexes to function as a fusion clamp (Chicka et al., 2008).

Unexpectedly, we found a dramatic enhancement in the rate of spontaneous vesicle release far beyond that observed in syt1\(^{-/-}\) null mutants when we rescued with transgenic proteins carrying mutations of Ca\(^{2+}\)-binding residues in both C2 domains (C2A*-C2B\(^{*}\), Fig. 5). Unlike the Ca\(^{2+}\)-dependent nature of spontaneous release at mammalian synapses (Xu et al., 2009; Kochubey and Schneggenburger, 2011), Ca\(^{2+}\)-dependent changes in mEJP frequency within a compatible

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**Figure 9.** Multimerization of wild-type and C2A*-C2B* Syt1. A, Western blot with anti-GFP antibodies is shown to demonstrate Ca\(^{2+}\)-independent and Ca\(^{2+}\)-dependent binding of endogenous GFP-tagged Syt1, purified from adult head lysates, to GST-fused wild-type (C2A-C2B) or Ca\(^{2+}\)-binding defective (C2A*-C2B*) Syt1. Fly head extracts are incubated with GST-fused Syt1 in the absence (EGTA, 2 mM) or presence of Ca\(^{2+}\) at a ratio of 1 or 10 mM. A, Anti-GFP Western blot with wild-type Syt1-His6 products indicated with arrows (top two bands) and a bracket (a single bottom band), respectively.
range (0.2–2.0 mM) of external [Ca\(^{2+}\)] at Drosophila NMJs has not been observed. As such, how can the dual Ca\(^{2+}\)-binding mutations of Syt 1 dramatically alter spontaneous release at Drosophila NMJs? Recently, conformational changes in C2 domain structure associated with Ca\(^{2+}\) binding have been suggested based on crystallization studies (Fuson et al., 2007). Indeed, we observed a change in the size of a protease-sensitive breakdown product previously described for Syt1 (Littleton et al., 1993) in syt1\(^{-/-}\) null mutants rescued with C2A*-C2B* (Fig. 2), suggesting subtle conformational changes in Syt1 structure. Ca\(^{2+}\)-binding mutations neutralize negatively charged aspartate residues (i.e., C2A*-C2B*), somewhat similar to the effect of bound Ca\(^{2+}\) ions. If these Ca\(^{2+}\)-binding mutations in the C2 domains induce structural changes, it might alter Ca\(^{2+}\)-independent interactions between Syt1 and SNARE complexes to increase the frequency of spontaneous vesicle release. It is unlikely that the effect of C2A*-C2B* on mEJP frequency would be due solely to the rescue of the docking and endocytosis defects observed in syt1\(^{-/-}\) mutants, as wild-type C2A-C2B transgenes also rescue these defects but did not induce a dramatic elevation in spontaneous fusion.

**Physiological significance of Syt1 multimerization**

Although the Syt family can form multimers in vitro, the relevance of such multimeric complexes on synaptic transmission in vivo has remained unclear. Different Syt family members can form homodimers via their N-terminal cysteine residues in a Ca\(^{2+}\)-independent manner (Fukuda et al., 1999; Bai et al., 2000; Fukuda et al., 2001), whereas Ca\(^{2+}\)-independent self-association and formation of heterodimers between different Syt family members are linked to activity of the C2B domain (Chapman et al., 1996; Damer and Creutz, 1996; Sugita et al., 1996; Osborne et al., 1999; Desai et al., 2000). Genetic analyses in Drosophila have suggested Syt oligomerization may regulate synaptic transmission. Mutations in the C2B domain that alter Syt1 oligomerization (Syt\(^{AD3}\)) (DiAntonio and Schwarz, 1994; Littleton et al., 1994; Fukuda et al., 2000) disrupt synaptic vesicle release (Littleton et al., 2001), although the effects of this mutation on phosphoinositide and SNARE binding, as well as defects in interactions with endocytosis regulators, might also contribute to the inability of the protein to control fusion.

The effects of the C2A*-C2B* transgene on release in the null versus wild-type backgrounds argue that the mutant form of Syt1 may form multimers with native Syt1 in vivo to generate a complex with unique properties. In the absence of endogenous Syt1, the C2A*-C2B* mutant failed to rescue any aspect of evoked release but strongly activated spontaneous fusion, suggesting that Ca\(^{2+}\)-binding defective Syt1 at rest was fusion-prone (Fig. 5). In contrast, when overexpressed with wild-type Syt1, there was no change in mEJP frequency, indicating that a multimer of native Syt1 and C2A*-C2B* Syt1 may be able to effectively clamp spontaneous release (Fig. 7B). In addition, this complex would be able to dramatically enhance evoked release (Fig. 7A). We hypothesize that overexpression of C2A*-C2B* allows this fusogenic version of Syt1 to multimerize with endogenous Syt1 in both Ca\(^{2+}\)-independent and Ca\(^{2+}\)-dependent manners in vivo, as suggested by binding assays (Fig. 9). These heteromultimers exhibit characteristics of both Syt1 molecules: they are more effective in Ca\(^{2+}\)-dependent vesicle fusion, as evidenced by increased release probability (Fig. 7D) and Ca\(^{2+}\) sensitivity (Fig. 7C) while maintaining a clamping function provided by endogenous Syt1 to reduce Ca\(^{2+}\)-independent spontaneous fusion (compare Figs. 7B and 5). Although additional studies will be required to confirm that the multimeric Syt1 complex exists in vivo, our data indicate that the different modes of synaptic release, Ca\(^{2+}\)-independent spontaneous fusion and Ca\(^{2+}\)-dependent synchronous vesicle release, are likely to be regulated by multimerization of Syt1. In addition, our findings provide evidence that both C2 domains of Syt1 are uniquely required for the two forms of synaptic neurotransmitter release.

**References**


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