Depression of voltage-activated Ca\(^{2+}\) release in skeletal muscle by activation of a voltage-sensing phosphatase

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Phosphoinositides act as signaling molecules in numerous cellular transduction processes, and phosphatidylinositol-4,5-bisphosphate (PtdIns(4,5)\(_2\)) regulates the function of several types of plasma membrane ion channels. We investigated the potential role of PtdIns(4,5)\(_2\) in Ca\(^{2+}\) homeostasis and excitation–contraction (E-C) coupling of mouse muscle fibers using in vivo expression of the voltage-sensing phosphatases (VSPs) Ciona intestinalis VSP (Ci-VSP) or Danio rerio VSP (Dr-VSP). Confocal images of enhanced green fluorescent protein–tagged Dr-VSP revealed a banded pattern consistent with VSP localization within the transverse tubule membrane. Rhod-2 Ca\(^{2+}\) transients generated by 0.5-s-long voltage-clamp depolarizing pulses sufficient to elicit Ca\(^{2+}\) release from the sarcoplasmic reticulum (SR) but below the range at which VSPs are activated were unaffected by the presence of the VSPs. However, in Ci-VSP–expressing fibers challenged by 5-s-long depolarizing pulses, the Ca\(^{2+}\) level late in the pulse (3 s after initiation) was significantly lower at 120 mV than at 20 mV. Furthermore, Ci-VSP–expressing fibers showed a reversible depression of Ca\(^{2+}\) release during trains, with the peak Ca\(^{2+}\) transient being reduced by \(\sim30\%\) after the application of 10 200-ms-long pulses to 100 mV. A similar depression was observed in Dr-VSP–expressing fibers. Cav.1 Ca\(^{2+}\) channel–mediated current was unaffected by Ci-VSP activation. In fibers expressing Ci-VSP and a pleckstrin homology domain fused with monomeric red fluorescent protein (PLC\(_{\beta} \cdot\) PH-mRFP), depolarizing pulses elicited transient changes in mRFP fluorescence consistent with release of transverse tubule–bound PLC\(_{\beta} \cdot\) PH domain into the cytosol; the voltage sensitivity of these changes was consistent with that of Ci-VSP activation and recovery occurred with a time constant in the 10-s range. Our results indicate that the PtdIns(4,5)\(_2\) level is tightly maintained in the transverse tubule membrane of the muscle fibers, and that VSP-induced depletion of PtdIns(4,5)\(_2\) impairs voltage-activated Ca\(^{2+}\) release from the SR. Because Ca\(^{2+}\) release is thought to be independent from InsP\(_3\) signaling, the effect likely results from an interaction between PtdIns(4,5)\(_2\) and a protein partner of the E-C coupling machinery.

INTRODUCTION

Muscle contraction is initiated when action potentials fired at the end-plate of the muscle cells propagate throughout the transverse tubule system and reach a region called the triad where the transverse tubule membrane comes into close apposition with two terminal cisternae of SR. There, transverse tubule depolarization triggers a conformational change of the dihydropyridine receptor (DHPR; the Cav.1 protein), which gates open the Ca\(^{2+}\) release channel (type 1 RyR [RyR1]) present in the adjacent SR membrane, through a protein–protein conformational coupling process: Ca\(^{2+}\) gets massively released from the SR into the cytosol, which increases the concentration of Ca–troponin C complex, triggering contraction (see Ríos et al., 1992; Schneider, 1994; Melzer et al., 1995). The process is rapidly and fully reversible so that upon membrane repolarization, muscle relaxation occurs driven by ATP-fuelled SR Ca\(^{2+}\) uptake. Although the remarkable reliability of the DHPR–RyR1 coupling keeps Ca\(^{2+}\) release under the strict control of the membrane potential, there are possibilities for modulation of this process by several candidate molecules and accessory proteins (Dulhunty, 2006; Treves et al., 2009). For many of them, the physiological relevance of this modulation at the intact cell level remains unclear. Phosphatidylinositol 4,5-bisphosphate (PtdIns(4,5)\(_2\)) is known to play a critical role in a wide diversity of cellular functions by acting either as substrate of phospholipase C to produce inositol-trisphosphate (Ins(1,4,5)\(_3\)) and diacylglycerol, or by acting as a direct lipid messenger through interactions with specific
motifs of proteins including several types of ion channels or by being the precursor of other phosphoinositide messengers with an analogous function.

In skeletal muscle, it has been generally agreed for ~20 years that there is little room for the prospect that Ins(1,4,5)P3 plays a direct role in excitation–contraction (E-C) coupling, as recently revisited by Blaauw et al. (2012). It should be mentioned though that this does not exclude the potential for Ins(1,4,5)P3 to be involved in Ca2+ signals with a physiological purpose other than contraction, either in a voltage-dependent (Casas et al., 2010; Jorquera et al., 2013) or voltage-independent manner (Tjondrokoesoemo et al., 2013). On the other hand, considering the growing number of proteins and specifically of voltage-dependent and voltage-independent ion channels that are sensitive to the PtdIns(4,5)P2 level in the plasma membrane, it was of strong interest to investigate whether the function of the E-C coupling molecular machinery would be dependent on PtdIns(4,5)P2 level. To this aim, we have expressed in vivo, in adult differentiated muscle fibers from mouse, a voltage-sensing phosphatase (VSP) that dephosphorylates PtdIns(4,5)P2 upon strong membrane depolarization (Murata et al., 2005). VSP, first discovered in ascidian Ciona intestinalis and later on in zebrafish (Danio rerio VSP [Dr-VSP]; Hossain et al., 2008), appeared as the first identified members of nonchannel proteins whose activity is regulated by membrane potential. This tool offers the possibility to trigger a rapid depletion of the PtdIns(4,5)P2 pool in the plasma membrane. We thus aimed at testing the consequences of triggering the VSP enzymatic activity on E-C coupling. Results demonstrate that activation of the phosphatase depresses voltage-activated Ca2+ release, revealing a role for PtdIns(4,5)P2 in the proper E-C coupling function.

**MATERIALS AND METHODS**

All experiments and procedures were performed in accordance with the guidelines of the local animal ethics committee of University Lyon 1, of the French Ministry of Agriculture (87/848), and of the European Community (86/609/EEC).

**In vivo transfection**

Expression was achieved by in vivo plasmid injection followed by electroporation, as described previously (Legrand et al., 2008; Weiss et al., 2010). Plasmids encoding the following proteins were used: Dr-VSP N-terminally tagged with EGFP, Dr-VSP and C. intestinalis VSP (Ci-VSP) in a bicistronic p-IRES-EGFP expression vector, and mRFP-tagged PLCδ3-PH domain (provided by T. Balla, National Institutes of Health, Bethesda, MD). In brief, 6–16-wk-old Swiss OF1 male mice were used. Transfection was performed in the flexor digitorum brevis (fdb) and interosseus muscles of the animals. Mice were anaesthetized with isoflurane inhalation using a commercial delivery system (Univentor 400 Anesthesia Unit; Univentor). 20 µl of a solution containing 2 mg/ml hyaluronidase dissolved in sterile saline was then injected into the footpads of each hind paw. 1 h later, the mouse was re-anaesthetized by isoflurane inhalation. A total volume of 20 µl of a solution containing 50 µg of plasmid DNA diluted in NaCl 9% was then injected into the footpads of the animal. After the injection, two gold-plated stainless steel acupuncture needles connected to the electroporation apparatus were inserted under the skin, near the proximal and distal portion of the foot, respectively. The standard protocol that we used consisted in 20 pulses of 200-V/cm amplitude and 20-ms duration delivered at a frequency of 2 Hz by a square wave pulse generator (BTX ECM 830; Harvard Apparatus). Muscle fiber isolation and experimental observations and measurements were performed 7–10 d later.

**Preparation of isolated muscle fibers**

Single fibers were isolated from the fdb and interosseus muscles from mice using a previously described procedure (Jacquemond, 1997). In brief, mice were killed by cervical dislocation before removal of the muscles. Muscles were treated with collagenase (type 1; Sigma-Aldrich) for 60 min at 37°C. Single fibers were then obtained by triturating the muscles within the experimental chamber. They were dispersed on the glass bottom of a 50-mm-wide culture µ-dish (Biovalley). For intracellular Ca2+ measurements under voltage-clamp conditions, fibers were first partially insulated with silicone grease so that only a 50–100-µm-long portion of the fiber extremity was left out of the silicone, as described previously (Jacquemond, 1997). The Ca2+-sensitive fluorescent indicator rhod-2 was then introduced into the myoplasm by diffusion through the tip of the voltage-clamp pipette (see below). For all experimental situations, EGFP-negative (referred to as VSP-negative) fibers isolated from the same muscles were used as control. All experiments were performed at room temperature (20–22°C).

**Electrophysiology**

A patch-clamp amplifier (RK-400; Bio-Logic) was used in whole-cell voltage-clamp configuration. Command voltage-pulse generation was achieved with an analogue–digital converter (Digitida 1440A; Axon Instruments) controlled by pClamp 9 software (Axon Instruments). Fibers were bathed in the TEA-containing extracellular solution (see Solutions). Voltage clamp was performed with a micropipette filled with the rhod-2-containing intracellular-like solution (see Solutions). The tip of the micropipette was inserted through the silicone within the insulated part of the fiber and was crushed against the bottom of the chamber to ease intracellular equilibration. Analogue compensation was adjusted to further decrease the effective series resistance. Unless otherwise specified, membrane-depolarizing steps were applied from a holding command potential of ~80 mV. For charge movement measurements, membrane current records were obtained in response to 100-ms-long depolarizing pulses of increasing amplitude from a holding potential of 0 mV. Removal of the linear leak and capacitive components of the current changes elicited by a depolarizing pulse was achieved using previously described procedures with record portions during pulses that were in some cases further corrected for sloping baseline (Collet et al., 2003; Pouvreau and Jacquemond 2005). Even with a depolarized holding potential, several fibers remained ineligible for charge movement analysis because of residual contaminating outward currents activated upon depolarization. When measuring Ca2+ transients in response to single depolarizing steps, a period of 30 s was allowed between two consecutive pulses. When the trains of 20 200-ms-long pulses (see Fig. 4) were applied, an interval of 1 min was allowed.

**Confocal imaging**

All experiments were conducted using a confocal microscope (LSM 5 Exciter; Carl Zeiss) equipped with a 63× oil-immersion objective (numerical aperture, 1.4). EGFP excitation was provided by the 488-nm line of an argon laser, and a 505-nm long-pass filter was used on the detection channel. For detection of either rhod-2 or PLCδ3-PH-mRFP fluorescence, excitation was...
from the 543-nm line of a HeNe laser and fluorescence was collected above 560 nm. Intracellular Ca\(^{2+}\)-related rhod-2 fluorescence changes were imaged by using the line-scan mode (x,t) of the system with the line parallel to the longitudinal fiber axis. Images were taken with a scanning frequency of 1.15 ms per line. PLC\(_{δ1}\)PH-mRFP fluorescence was detected either in (x,y) or (x,t) mode. For measurements of the changes in transverse tubule membrane voltage upon voltage-clamp depolarization, muscle fibers were incubated for 30 min in the presence of 10 \(\mu\)M di-8-anepps before voltage clamp was achieved. Unless otherwise stated, di-8-anepps fluorescence was measured with the line-scan mode of the confocal microscope (1.93 or 1.15 ms per line) using the same configuration as for rhod-2 and mRFP, but with the pinhole fully open. Image processing and analysis was performed using ImageJ (National Institutes of Health) and Origin (OriginLab Corporation) software.

### Results

**Expression of VSP in muscle fibers.** Transmitted light images and corresponding confocal images of a portion of muscle fibers expressing Ci-VSP using the pIRES-EGFP plasmid (A) and Dr-VSP N-terminally tagged with EGFP (B). In B, the white trace superimposed on the green image shows the typical banded pattern of the fluorescence along the longitudinal axis of the fiber.

Data values are presented as means ± SEM for \(n\) fibers. Statistical significance was determined using a Student’s \(t\) test (*, \(P \leq 0.05\)).

### Online supplemental material

Fig. S1 shows results from measurements of intramembrane charge movement in VSP-negative and VSP-positive fibers. Fig. S2 presents results from measurements of changes in transverse tubule membrane voltage using the dye di-8-anepps. Fig. S3 shows the voltage-dependent properties of the DHPR Ca\(^{2+}\) current in VSP-negative and VSP-positive fibers. Results from measurements of intramembrane charge movement, of di-8-anepps fluorescence, and of DHPR Ca\(^{2+}\) current are described in detail in the text accompanying Figs. S1, S2, and S3, respectively. Videos 1 and 2 show a sequence of confocal images of PLC\(_{δ1}\)PH-mRFP fluorescence from two fibers also expressing Ci-VSP and depolarized by 5-s-long pulses. The online supplemental material is available at http://www.jgp.org/cgi/content/full/jgp.201411309/DC1.
factors used in Fig. 4, mean fiber diameter was 51.5 ± 2.8 µm (n = 17) and 49.5 ± 2.0 µm (n = 17), respectively; corresponding mean measured capacitance was 1,599 ± 120 pF (n = 21) and 1,544 ± 210 pF (n = 19), which, considering that a similar length of fiber was always under voltage clamp, indicates that there was no significant difference in transverse tubule density between VSP-negative and Ci-VSP–positive fibers.

Although expression of EGFP with the pIRES plasmid produced an expected homogenous fluorescence, expression of the EGFP–Dr-VSP fusion protein revealed a clear double-striped transverse pattern with an ~2-µm spacing interval, reminiscent of the triadic area. This pattern does not disclose which membrane compartment of the triad is targeted by the VSP. However, considering that previous works in various expression systems established that VSPs localize in the plasma membrane, it is very likely that under our conditions, the striated pattern corresponded to the transverse tubule membrane system of the muscle fibers.

With the aim of formally establishing the VSP protein localization in the transverse tubule membrane, we attempted to measure intramembrane charge movement in VSP-negative and VSP-positive fibers maintained at a holding voltage of 0 mV. These measurements could not be made entirely acceptable because several fibers were not suitable for analysis as a result of remaining voltage-activated contaminating outward currents. Furthermore, a transient inward current component at the onset of the depolarizing pulses complicated the analysis. For these

![Figure 2](image-url). Voltage-activated Ca²⁺ release in VSP-expressing fibers. (A) Line-scan images of depolarization-induced Ca²⁺ release in a VSP-negative fiber (left) and in a Ci-VSP–expressing fiber (right); fibers were depolarized from −80 to 10 mV (traces on top). (B) Ca²⁺ transients (rhod-2 F/F₅₀ thick traces) and corresponding rate of Ca²⁺ release (thin red traces) in response to pulses from −80 mV to the indicated values. (C) Peak Ca²⁺ release versus voltage in VSP-negative fibers (n = 9) and in Ci-VSP–expressing fibers (n = 6). Error bars represent ± SEM. (D) Average Ca²⁺ release in response to a pulse from −80 to 10 mV in VSP-negative fibers (line) and in Ci-VSP–expressing fibers (blue squares).
Ca\textsuperscript{2+} release in response to single depolarizing steps in VSP-expressing fibers

SR Ca\textsuperscript{2+} release is physiologically activated within a range of membrane voltages that is more negative than the one needed to activate Ci-VSP or Dr-VSP. Our main goal was to take advantage of this shift to compare the properties of Ca\textsuperscript{2+} transients elicited by voltage pulses that would maximally activate Ca\textsuperscript{2+} release with or without activating the VSP. We first tested whether presence of the VSP proteins per se in the transverse tubule membrane affects the properties of Ca\textsuperscript{2+} release independently from the phosphatase activity. Fig. 2 A shows illustrative examples of line-scan confocal images of rhod-2 fluorescence taken from a VSP-negative fiber (left) and from a fiber expressing Ci-VSP (right). Both fibers were step-depolarized by a 0.5-s-long depolarization from \(-80\) to 10 mV. Fig. 2 B shows the time course of change in rhod-2 fluorescence (thick traces) and the corresponding calculated rate of release (thin traces) in response to 0.5-s-long pulses of increasing amplitude, in these two fibers. Expression of Ci-VSP had no striking consequence on the Ca\textsuperscript{2+} signals: in both fibers, Ca\textsuperscript{2+} release was activated at a similar threshold voltage level and yielded the classical waveform characterized by an early peak that rapidly decayed toward a lower level. Fig. 2 C presents mean values for peak Ca\textsuperscript{2+} release versus voltage in VSP-negative fibers (\(n = 9\)) and in Ci-VSP–expressing fibers (\(n = 6\)): there was no statistical difference between the values in the two groups. The same measurements performed in three fibers expressing Dr-VSP gave mean values in the same range (not depicted). Fig. 2 D shows the average Ca\textsuperscript{2+} release trace in response to a 0.5-s-long pulse to 10 mV in VSP-negative fibers and in Ci-VSP–expressing fibers. There was no sign of any difference in the time course of Ca\textsuperscript{2+} release in the VSP-expressing fibers.

According to previous works, substantial depletion of plasma membrane PtdIns(4,5)P\textsubscript{2} requires at least several hundred milliseconds of VSP activation by a strong membrane depolarization, whereas subsequent recovery from depletion occurs over a time scale of seconds to tens of seconds (see, for instance, Sakata et al., 2011). Because upon membrane depolarization SR Ca\textsuperscript{2+} release exhibits an early peak that falls within 10–20 ms toward a low, slowly declining level, we did not expect a sustained strong depolarization to be the optimal protocol to reveal a potential effect of VSP activation, as PtdIns(4,5)P\textsubscript{2} would become substantially depleted at a time when Ca\textsuperscript{2+} release is very low. Furthermore, such long pulses cannot

Figure 3. Ca\textsuperscript{2+} transients in VSP-expressing fibers depolarized by large pulses. (A) Voltage-pulse protocol. (B and C) Corresponding F/F\textsubscript{0} rhod-2 traces in a Ci-VSP–negative and in a Ci-VSP–positive fiber, respectively. Arrows point to the F/F\textsubscript{0} level 3 s after the onset of the pulse. (D) Mean values for the ratio of the initial peak rhod-2 Ca\textsuperscript{2+} transient in response to the pulse to 120 mV to the initial peak value in response to the pulse to 20 mV in VSP-negative (\(n = 11\)) and Ci-VSP–positive fibers (\(n = 8\)). (E) Mean values for the ratio of the rhod-2 Ca\textsuperscript{2+} level 3 s after the onset of the pulse to 120 mV to the corresponding value during the pulse to 20 mV. Error bars represent ± SEM. *, \(P \leq 0.05\).
be repeated at a frequency that would seem sufficiently high to avoid PtdIns(4,5)P₂ repletion between pulses, as the time for recovery of Ca²⁺ release from SR Ca²⁺ depletion, and also to some extent from voltage-dependent inactivation, precludes repeating such pulses with a short interval. We nevertheless did compare Ca²⁺ transients triggered by 5-s-long depolarizing pulses to 20 mV (non-VSP-activating pulse) and to 120 mV (VSP-activating pulse) in VSP-negative and VSP-positive fibers. Fig. 3 (B and C) shows rhod-2 fluorescence transients elicited by stepping the membrane potential from −80 to 20 mV, then from −80 to 120 mV, and then again from −80 to 20 mV in a Ci-VSP-negative fiber and in a Ci-VSP-positive fiber, respectively. The three fluorescence transients looked quite similar in the VSP-negative fiber, but in the VSP-expressing fiber, the fluorescence signal appeared to be less sustained late during the pulse to 120 mV as compared with the level during the bracketing pulses to 20 mV. Fig. 3 (D and E) shows mean values for the ratio of the initial peak and of the late (3 s after the beginning of the pulse) rhod-2 Ca²⁺ transients in response to the pulse to 120 mV versus corresponding values in response to the pulses to 20 mV in VSP-negative (n = 11) and Ci-VSP-positive fibers (n = 8). In each fiber, initial and late F/F₀ values for the pulse to 120 mV were divided by the average of the two respectively corresponding bracketing values measured in response to the pulses to 20 mV. The mean ratio for initial peak Ca²⁺ transient did not statistically differ between the two groups of fibers. In contrast, the mean ratio for the Ca²⁺ level 3 s after the beginning of the pulse was significantly depressed in Ci-VSP-expressing fibers as compared with the mean value in VSP-negative fibers (P = 0.007).

The strong depolarizing pulses used to activate the VSP inevitably triggered substantial activation of outward K⁺ current, which was expected to affect the quality of the
voltage control. To estimate the actual voltage reached in the transverse tubule membrane of the voltage-clamped portion of fiber during these pulses, we measured the changes in fluorescence of the voltage-sensitive dye di-8-anepps in nontransfected muscle fibers. Results from these measurements are presented in Fig. S2. They suggest that during command pulses to 100 or 120 mV, the actual transverse tubule voltage reached ~60 mV, sufficient to substantially activate Ci-VSP.

**Ca**\(^{2+}\) release in response to trains of depolarizing steps in Ci-VSP–expressing fibers

To maximize the likelihood of severely depleting PtdIns(4,5)P\(_2\) through VSP activation while maintaining the potency to trigger substantial Ca\(^{2+}\) release, we used a protocol consisting in successive 200-ms-long depolarizing pulses applied every 2 s. Although under such conditions peak Ca\(^{2+}\) release decreased over time as pulses were applied, a significant activity could be maintained over a period of ~1 min (Fig. 4). Fig. 4 A shows the exact protocol used in each fiber: a 200-ms-long pulse was applied 10 times from -80 to 10 mV and then 10 times again to either 10 mV (control protocol) or to 100 mV (test, VSP-activating protocol). The 10 first Ca\(^{2+}\) transients were used to assess the reproducibility of the changes in Ca\(^{2+}\) in the test versus the control record in response to the same pulses that did not activate the VSP. The next 10 pulses were anticipated to reveal the effect of VSP activation in the test record. B and D in Fig. 4 show such pairs of records from a VSP-negative fiber and from a Ci-VSP–expressing fiber, respectively. In both fibers, as the successive pulses were applied, Ca\(^{2+}\) transients were triggered and decayed to an elevated level. In the VSP-negative fiber, the two records looked quite similar. In contrast, in the Ci-VSP–expressing fiber, there was a progressive drop in the amplitude of the Ca\(^{2+}\) transients as pulses to 100 mV were applied. Independent of the presence of VSP, there was fiber to fiber variability in the overall time course of change in peak and baseline Ca\(^{2+}\) levels along the records. For instance, the fact that the peak rhod-2 transient appeared more sustained along the last 10 pulses in Fig. 4 D as compared with Fig. 4 B was absolutely not a reproducible feature of the VSP-expressing fiber (see, for instance, Fig. 6). Furthermore, in a given fiber the actual amplitude of peak Ca\(^{2+}\) transients in response to the first 10 pulses also could somewhat vary between the control and the test record. For analysis, successive peak F/\(F_0\) values during the test record were thus divided by the corresponding values in the control record; values for this ratio were then normalized to the ratio value corresponding to the first Ca\(^{2+}\) transient of the train. The right-end graph in Fig. 4 (B and D) shows values for the ratio plotted versus the pulse number for the two fibers. Corresponding mean values from 21 VSP-negative fibers and 19 Ci-VSP–expressing fibers are reported in the left panel of Fig. 4 F. Although in the VSP-negative fibers the ratio remained close to unity for all Ca\(^{2+}\) transients, there was a clear drop in the ratio as pulses to 100 mV were applied in the Ci-VSP–expressing fibers. Statistical comparison of the values revealed a significant difference between VSP-negative and Ci-VSP–expressing fibers, starting from pulse number 13 (third pulse to 100 mV). For instance, the mean ratio value corresponding to the last pulse in the protocols was 0.73 ± 0.06 and 0.95 ± 0.05 for Ci-VSP–positive fibers and VSP-negative fibers, respectively (\(P = 0.006\)). Statistical difference was also tested versus the hypothesis of the ratio being 1. For the VSP-negative fibers, none of the mean ratio values significantly differed from 1, whereas for the Ci-VSP fibers, all ratio values starting from pulse number 12 were significantly lower than 1.

A similar analysis was performed from the peak values of the Ca\(^{2+}\) release flux calculated from the rhod-2 traces. Flux traces corresponding to the rhod-2 signals from the VSP-negative and VSP-expressing fibers illustrated in Fig. 4 are shown in C and E, with the right-side graph showing values for the test over control ratio plotted versus the pulse number. Corresponding mean values are reported in the right panel in Fig. 4 F. Mean values from the VSP-expressing fibers were significantly depressed as compared with values in VSP-negative fibers starting from pulse number 13.

We asked whether the presence and/or activation of VSP had consequences on the membrane current flowing during the pulses. We measured membrane current near the end of each depolarizing pulse applied during

![](https://example.com/image.png)

**Figure 5.** Membrane current during trains of depolarizing steps in VSP-negative fibers and Ci-VSP–expressing fibers. Mean value for the membrane current measured at the end of each depolarizing pulse during the control and test protocols shown in Fig. 4. The horizontal axis is positioned at the zero-current level. Error bars represent ± SEM.
the control and test protocol, and values were normalized to fiber capacitance. Corresponding mean values are presented in Fig. 5. There was no indication that either the presence of Ci-VSP in the membrane or its activation by the pulses to 100 mV produced any modification of the membrane current.

To test whether the depressing effect of Ci-VSP activation on Ca\(^{2+}\) release was reversible and repeatable, two test protocols were applied, bracketed by control protocols, in a subset of fibers. This appeared to be the case, as Fig. 6 illustrates. Fig. 6 B shows F/F\(_{0}\) rhod-2 traces elicited in a Ci-VSP–expressing fiber alternatively challenged by a control and a test protocol (Fig. 6 A). Fig. 6 C shows mean values for the peak F/F\(_{0}\) values during the test 1, control 2, and test 2 records, all divided by the corresponding values in the control 1 record. Values are from 12 Ci-VSP–expressing fibers. The drop in Ca\(^{2+}\) release elicited by the first set of pulses to 100 mV was transient and could be triggered again by a second series of the same pulses, consistent with reversible reduction in the level of a molecule with agonistic properties toward Ca\(^{2+}\) release.

Ca\(^{2+}\) current after strong depolarizing pulses in Ci-VSP–expressing fibers

The above data are consistent with the possibility that activation of VSP in the transverse tubule membrane affects Ca\(^{2+}\) release. We examined whether the function of Cav1.1, which acts both as voltage sensor for E-C coupling and as voltage-dependent Ca\(^{2+}\) channel, would be affected after VSP activation. For this, we measured the Ca\(^{2+}\) current in fibers challenged by a double-pulse protocol. The membrane voltage was first stepped from -80 to 20 mV for 5 s (prepulse) and then, after a 1-s delay, from -80 to 20 mV for 1 s (test pulse). The double pulse was then applied with the prepulse to 120 mV to activate the VSP and then again with the prepulse to 20 mV as a bracketing control. In each fiber, the whole protocol was repeated with a 2-s and with a 5-s interval between the prepulse and the test pulse. Corresponding membrane current traces from a Ci-VSP–expressing fiber are shown in Fig. 8 (A–C). In each panel, the two membrane current records with the prepulse to 20 mV are in black, and the record with the prepulse to 120 mV is in red.

Ci-VSP expression per se did not affect the amplitude of the Ca\(^{2+}\) current: the mean peak value of the current record) when the pulses to 100 mV were applied. As a consequence, none of the mean ratio values significantly differed from the corresponding ones in the VSP-negative fibers. Still, when testing the mean values versus the hypothesis of the ratio being 1, values for pulses number 15 and above were significantly depressed. Dr-VSP appeared thus less efficient than Ci-VSP in depressing Ca\(^{2+}\) release, but this was expected because it requires more positive voltage steps to be activated.
significantly differ between VSP-negative fibers and either Ci-VSP– or Dr-VSP–expressing fibers. Values were, however, significantly larger in Ci-VSP–expressing fibers than in Dr-VSP–expressing fibers at 20 (P = 0.039), 30 (P = 0.009), and 40 mV (P = 0.003). Because Ci-VSP would be activated to some extent at these voltages, this may be an indication that Ca$^{2+}$ current inactivation is sensitive to the consequences of the phosphatase activity.

**PtdIns(4,5)P$_2$ level after depolarization of Ci-VSP–expressing fibers**

To explicitly assess in our conditions the ability of VSP activation to deprive plasma membrane PtdIns(4,5)P$_2$, we coexpressed Ci-VSP (using the pIRES-EGFP plasmid) together with the PtdIns(4,5)P$_2$-selective PLC$_{δ1}$-PH domain (Stauffer et al., 1998; Várnai and Balla, 1998) tagged with mRFP, and we followed the corresponding changes in fluorescence upon membrane depolarization. For simplicity, we will refer to PLC$_{δ1}$-PH-mRFP fluorescence as “mRFP fluorescence.” Fig. 9 A shows confocal images of GFP and of mRFP fluorescence from such a co-transfected muscle fiber. The enlarged view of the mRFP fluorescence on the right, together with the graph below which is reporting the fluorescence intensity along a rectangular region of interest, clearly shows that mRFP yielded a characteristic triadic pattern, namely double-banded transverse-oriented striations spaced by ~2 µm.

The closed circles in Fig. 9 B show the time course of change in mRFP fluorescence averaged over an entire given area of the fiber while applying 5-s-long depolarizing pulses according to the protocol shown on top; for this, a confocal $x,y$ image was taken every 1.97 s. The sequence of images at lower resolution is presented as Video 1. The open circles in Fig. 9 B show the time course of change in mRFP fluorescence measured afterward, during the 5-s-long prepulse to 20 mV was $-2.5 \pm 0.6$ A/F and $-3.3 \pm 0.6$ A/F in VSP-negative ($n = 7$) and VSP-positive fibers ($n = 8$), respectively, not significantly different. The peak amplitude of the calcium current during the test pulse was depressed as compared with its amplitude during the prepulse to 20 mV, as expected from only partial recovery from voltage-dependent inactivation. Interestingly, the prepulse to 120 mV actually seemed to slightly enhance the Ca$^{2+}$ current amplitude during the test pulse as compared with the prepulse to 20 mV, an effect that was observed in both VSP-negative and VSP-positive fibers. Reasons for this effect are currently being explored, independent from the present work. In any case, we found no indication that activation of the VSP had an effect on the Ca$^{2+}$ channel activity. Fig. 8 D shows mean values for the ratio of the Ca$^{2+}$ current amplitude after the prepulse to 120 mV to its amplitude after the prepulse to 20 mV (average of the two bracketing values) versus the pulse interval. Membrane current amplitudes were measured as the difference between the peak and the end-pulse level. There was no statistical difference between mean ratio values in VSP-negative and VSP-positive fibers. Although one cannot exclude that even the shortest interval at $-80$ mV (1 s) could allow some recovery from the consequences of the phosphatase activity, results provide no indication that Cav1.1 Ca$^{2+}$ current amplitude is a sensitive target of this activity. In a separate series of experiments, we compared the voltage dependence of the Ca$^{2+}$ current properties between VSP-negative and VSP-positive fibers (Fig. S3). Results provided again no indication that the peak amplitude and also the time to peak of the current would differ between VSP-negative fibers and Ci-VSP– and Dr-VSP–expressing fibers. Regarding the mean values for the time constant of current decay, they did not significantly differ between VSP-negative fibers and either Ci-VSP– or Dr-VSP–expressing fibers. Values were, however, significantly larger in Ci-VSP–expressing fibers than in Dr-VSP–expressing fibers at 20 (P = 0.039), 30 (P = 0.009), and 40 mV (P = 0.003). Because Ci-VSP would be activated to some extent at these voltages, this may be an indication that Ca$^{2+}$ current inactivation is sensitive to the consequences of the phosphatase activity.

**Figure 7.** Ca$^{2+}$ transients in response to trains of depolarizing steps in Dr-VSP–expressing fibers. (A) Control and test voltage-pulse protocols. (B) Rhod-2 F/F$_0$ traces recorded in response to the protocols shown in A in a Dr-VSP–positive fiber. (C) Mean values for the normalized ratio of peak F/F$_0$ during the test record to the corresponding peak F/F$_0$ during the control record, versus the pulse number in Dr-VSP–positive fibers ($n = 7$). Mean values for VSP-negative fibers are the same as in Fig. 4. Error bars represent ± SEM.
over a nearby fiber area, while no pulse was applied. Although we tried to keep laser excitation as low as possible, there was quite substantial mRFP photobleaching over time. Nevertheless, on top of photobleaching, clear positive changes in fluorescence were triggered by the largest depolarizing pulses. In Fig. 9 C, the time course of change in fluorescence associated with the depolarizing pulse protocol was corrected for photobleaching. To do so, values were divided by the time-corresponding ones in the subsequent record taken when no pulse was applied (closed circles in Fig. 9 C). As an alternative, a two-exponential function was fitted to the time course of baseline decay in fluorescence in the series of measurements taken while the voltage steps were applied; for this, only the 20 first and 20 last values in the trial were used for the fit. From this, a synthetic series of decaying values was generated (superimposed line plot in Fig. 9 B), which was then used to normalize fluorescence values associated with the depolarizing pulses. The result from this correction is shown as open circles in Fig. 9 C. The two correction procedures provided a very similar result: there was a clear transient rise in mRFP fluorescence in response to the pulses to 50, 90, and 110 mV. Identical measurements performed in three fibers isolated from a muscle expressing only the PLC\(\delta\)-PH domain and not the VSP showed absolutely no change in fluorescence upon membrane depolarization (not depicted).

A quantitative estimate of the kinetics of the depolarization-induced changes in mRFP fluorescence was made by fitting a single-exponential function to the time course of fluorescence increase upon membrane depolarization and of fluorescence recovery after membrane repolarization, when this could be reliably performed. This was intended to only provide an order of magnitude of the rate of changes, as photobleaching correction could not be perfectly accurate and corrupted to some extent the kinetics of voltage-induced mRFP changes. The time constant of rise estimated from data collected from four

![Figure 8](image-url)

**Figure 8.** \(\text{Ca}^{2+}\) current after strong depolarizing pulses in Ci-VSP-expressing fibers. In each panel, top traces show the two voltage-pulse protocols that were applied to the fiber; the protocol with prepulse to 120 mV (test) was bracketed by two protocols with prepulse to 20 mV (controls). (A–C) Superimposed membrane current records in response to the above shown protocols. Currents recorded during the two control protocols are in black, whereas current elicited by the test protocol is presented in red. In A, records are presented at both low (top) and high magnification (bottom). In B and C, only the high magnification views are presented. (D) Mean values for the ratio of \(\text{Ca}^{2+}\) current amplitude after the prepulse to 120 mV to its amplitude after the prepulse to 20 mV; values are plotted versus the pulse interval between the pre- and test pulses. Results are from seven VSP-negative and eight Ci-VSP-positive fibers. Error bars represent \(\pm\) SEM.
fibers challenged with a 20-s-long depolarizing pulse to 40 or 50 mV and to 100 or 110 mV was 14.8 ± 4 s and 7.5 ± 2 s, respectively. The time constant of mRFP fluorescence recovery after membrane repolarization was 14.3 ± 4.5 s after a pulse to 40 or 50 mV (n = 5) and 13.9 ± 3 s after a pulse to 90–110 mV (n = 6), respectively. The fact that the rate of rise increased with the amplitude of the depolarizing pulse further supports the conclusion that this signal results from voltage-evoked VSP enzyme activity. It is also worth noting that the rate of rise of the mRFP signal upon strong depolarization is much slower than the kinetics of Ca\(^{2+}\) release. This confirms our postulate (in relation with Fig. 3) that during a sustained depolarization, PtdIns(4,5)P\(_2\) becomes substantially depleted at a time when Ca\(^{2+}\) release is very low.

Spatially segregated distinct changes in PtdIns(4,5)P\(_2\) after Ci-VSP activation

Careful viewing of Video 1 reveals that the striated pattern of mRFP fluorescence tends to vanish during the strong depolarizing pulses. This effect of membrane depolarization upon the spatial distribution of mRFP fluorescence is examined in Fig. 10. Fig. 10 A shows three confocal images of mRFP fluorescence taken from another fiber before, during, and after a 5-s-long pulse to 50 mV. The corresponding whole sequence of successive images is presented as Video 2. The graph below each image in Fig. 10 A shows the fluorescence intensity profile along the highlighted rectangular area (Fig. 10 A, left). During the depolarizing pulse, the average fluorescence was slightly increased, accompanied by a clear attenuation of the transverse triadic profile, a phenomenon that was reversible after membrane repolarization. The fluorescence intensity at a given location of the profile during the pulse (Fluo\(_{+50}\)) was subtracted from its corresponding initial/resting intensity before the pulse (Fluo\(_{-80(1)}\)), and the difference is plotted versus the initial fluorescence intensity (Fluo\(_{-80(1)}\)) in the left panel of Fig. 10 B. The result shows a clear negative slope with the difference being positive for the lowest levels of initial/resting fluorescence intensity and negative for the largest. According to the standard interpretation of the banded intensity profile, within the limits of the confocal resolution (with respect to triadic membrane compartment versus cytosolic volume), lowest values of initial/resting fluorescence are likely to report a

![Figure 9](Image)

**Figure 9.** PLC\(_{\beta}\),PH-mRFP fluorescence in fibers expressing Ci-VSP. (A) Confocal images of a portion of a muscle fiber expressing Ci-VSP using the pIRES-EGFP plasmid and PLC\(_{\beta}\),PH-mRFP. The image on the right shows the PLC\(_{\beta}\),PH-mRFP fluorescence at higher magnification, and the graph below shows the fluorescence profile along the longitudinal axis of the highlighted rectangular region (yellow box). (B) Time course of change in PLC\(_{\beta}\),PH-mRFP fluorescence averaged over a given area of the fiber while applying 5-s-long depolarizing pulses according to the protocol shown on top (closed circles); superimposed time course of change in PLC\(_{\beta}\),PH-mRFP fluorescence measured subsequently over a nearby fiber area while no pulse was applied (open circles); synthetic trace generated from a two-exponential fit to the closed-circles record, using only the 20 first and 20 last values in the record for the fit (line). (C) Changes in fluorescence associated with the depolarizing pulse protocol after normalization by the record taken when no pulse was applied (open circles); changes in fluorescence associated with the depolarizing-pulse protocol after normalization by the synthetic record (open circles).
dominant cytosolic contribution, whereas highest values should encompass a more important triadic membrane contribution, which we will assume here to correspond to the transverse tubule. Accordingly, the depolarizing pulse induces a depression of transverse tubule–bound mRFP and an increase in cytosolic mRFP, consistent with translocation of the probe from the transverse tubule into the cytosol, most likely reporting reduction of transverse tubule PtdIns(4,5)P₂ level. In the right graph of Fig. 10 B, the fluorescence intensity at a given location of the profile during the pulse (Fluo+50) was subtracted from the corresponding intensity after the pulse (Fluo−80(2)) and the difference plotted versus the post-pulse fluorescence intensity (Fluo−80(2)). The result is very similar to the one in the left graph, consistent with return of the probe to the transverse tubule membrane upon membrane repolarization.

This spatially distinct effect of strong depolarizing pulses on mRFP fluorescence is examined in an alternative way in Fig. 10 C; here, the analysis shown in Fig. 9 (B and C) was performed using either only the high intensity pixels in the initial/resting image (which should report a larger transverse tubule contribution) or only low intensity pixels (which should report a larger cytosolic contribution). Consistently, in response to the strong depolarizing pulses, pixels of high initial intensity tended to experience a transient decrease in fluorescence in contrast to pixels of low initial intensity. A similar analysis was successfully achieved in three out of four muscle fibers that were challenged by this same pulse protocol. Fig. 10 D shows the mean relative peak change in mRFP fluorescence versus membrane potential calculated using either all pixels in the images or using only high intensity or low intensity initial pixels. Collectively, these results appear very consistent with voltage-activated translocation of the PLCδ1-PH probe from the triad into the cytosol, with a voltage dependence similar to that of Ci-VSP activation.

Figure 10. Spatially segregated distinct changes in PLCδ1-PH-mRFP fluorescence upon strong membrane depolarization in fibers expressing Ci-VSP. (A) Confocal images of a portion of a muscle fiber expressing Ci-VSP and PLCδ1-PH-mRFP. Images from left to right were taken before, during, and after a 5-s-long depolarizing pulse to 50 mV, respectively. The graph below each image shows the fluorescence intensity profile along the rectangular area highlighted in the image on the left. (B; left graph) Difference between the intensity at a given location of the fluorescence profile during the pulse (Fluo+50) and its corresponding intensity before the pulse (Fluo−80(1)) versus Fluo−80(1). (Right graph) Difference between the intensity at a given location of the fluorescence profile during the pulse (Fluo+50) and its corresponding intensity after the pulse (Fluo−80(2)) versus Fluo−80(2). (C) Result of the analysis similar to that shown in Fig. 9 C, except that pixels with high initial intensity and low initial intensity were separated; pixel selection was achieved by adjusting manually the threshold tool in ImageJ in the first image of the sequence. (D) Mean relative peak change in PLCδ1-PH-mRFP fluorescence versus membrane potential calculated from three fibers that experienced the pulse protocol shown in C; closed circles, open squares, and open circles correspond to values obtained using all, high intensity, and low intensity initial pixels, respectively. Error bars represent ± SEM.
One unclear feature of the mRFP signal is that if PLCβ₁-PH molecules simply translocate from membrane to cytosol, no change in the global fluorescence should occur. As there is no reason for the number of PH molecules available in the fibers to increase in response to the large depolarizing pulses, there has to be nonlinearity in the system that makes the fluorescence increase. We have no clear-cut explanation for this yet. There are two factors that may contribute to this effect. One possibility is that changes in the local microenvironment experienced by mRFP upon translocation from membrane to cytosol modify its fluorescence properties, as was suggested for PH constructs with CFP, YFP, or GFP (van der Wal et al., 2001), although the changes observed by these authors corresponded to a decreased intensity upon translocation to the cytosol. Another possibility is that the fluorescence intensity from the PH domain molecules bound to the transverse tubule membrane at rest underestimates its actual concentration; this could be enhanced by the fact that the confocal imaging system detects essentially the fluorescence from the cytosol, even in the regions of higher resting fluorescence, which we assume correspond to the transverse tubules.

**DISCUSSION**

We used VSP as a tool to deplete PtdIns(4,5)P₂ in the sarcolemma and transverse tubule membrane of skeletal muscle fibers. Results show that VSP can be expressed by in vivo electroporation in mouse muscle without disturbing the basic morphological and functional properties of the muscle fibers. VSP expresses and is active in the transverse tubule membrane of the transfected muscle fibers. PtdIns(4,5)P₂ visualized by expression of mRFP-tagged PLCβ₁-PH domain also localizes to the transverse tubule membrane. Activating VSP alters the localization of the PLCβ₁-PH domain in a way that is consistent with its translocation to the cytosol. Activating VSP reduces SR Ca²⁺ release during depolarizing pulses. This last point is the new message: PtdIns(4,5)P₂ depletion depresses calcium release.

Although an absolute quantification of the extent of VSP activation–induced PtdIns(4,5)P₂ depletion in the transverse tubule membrane was not possible with the mRFP probe, the quite extensive disappearance of the spatial distribution of the mRFP signal triggered by strong pulses and also during the control-pulse protocol, the fluorescence exhibited only a progressive decay. In contrast, the series of pulses to 100 mV during the test protocol were clearly associated with a transient increase of the fluorescence.

Figure 11. Changes in PLCβ₁-PH-mRFP fluorescence in Ci-VSP-expressing fibers during the train of depolarizing steps protocol. (A) PLCβ₁-PH-mRFP fluorescence detected in a fiber successively challenged by the above shown voltage-pulse protocols; fluorescence was measured in line-scan mode. The rightmost trace corresponds to the ratio of the sum of the two traces taken during a test train-pulse protocol and the sum of the two other traces. (B) Mean (±SEM; gray shading) change in fluorescence during the test protocol (n = 4); in each fiber, the fluorescence record during the test protocol was normalized by bracketing traces recorded while either applying no pulse or while applying a control protocol.
depolarizing pulses is likely to correlate with a substantial reduction of the membrane-bound PtdIns(4,5)P$_2$ level. One other quite remarkable feature of this signal is its transient nature with recovery occurring with a time constant in the 10-s range, which appears independent of the VSP-activating voltage. Assuming PtdIns(4)P to be the main PtdIns(4,5)P$_2$ precursor in the plasma membrane, this indicates that the transverse tubule membrane of muscle fibers is well equipped with PtdIns 5 kinase activity to face PtdIns(4,5)P$_2$ depletion and reconstitute the pool.

Upon depolarization VSPs dephosphorylate the 5’ position of PtdIns(3,4,5)P$_3$ and PtdIns(4,5)P$_2$ and the 3’ position of PtdIns(3,4)P$_2$ (Kurokawa et al., 2012). In the present conditions, we tend to favor PtdIns(4,5)P$_2$ as the active molecule because of its rich history of function in regulating ion channels and transporters in the plasma membrane of various cell types, and also because of our results with the PtdIns(4,5)P$_2$-selective PLC$_5$·PH probe. However, we cannot exclude a possible contribution from the two other substrates.

Another point that is worth stressing is that although we assumed that VSP was negligibly activated during pulses to 20 mV, this was likely not entirely the case, specifically with Ci-VSP, which yielded the most negative voltage dependence. However, because our major aim was to compare Ca$^{2+}$ release during strong VSP activation to Ca$^{2+}$ release without (or with less) VSP activation in a same muscle fiber, Ca$^{2+}$ release needed to be maximally activated with respect to its voltage dependence in both cases; so, pulses to 10 or 20 mV were required in the non-VSP-activating situation.

The question of how Ca$^{2+}$ release can be affected by PtdIns(4,5)P$_2$ depletion is then the upcoming challenge. Although we are tempted to dismiss a role of PtdIns(4,5)P$_2$ as precursor of the Ca$^{2+}$-mobilizing molecule Ins(1,4,5)P$_3$ because of the lines of evidence denying a role for this pathway in the control of E-C coupling–related Ca$^{2+}$ signals in differentiated muscle fibers (see Foster, 1994; Blaauw et al., 2012), we cannot unequivocally reject the possibility of a contribution of this process to the VSP effect we observe.

The alternative is to consider an interaction of PtdIns(4,5)P$_2$ with a protein partner of the E-C coupling machinery. Interestingly, in the 1990s several studies using skinned fibers, SR membrane preparations, and RyR channels incorporated into a phospholipid bilayer showed that RyR1 activity and Ca$^{2+}$ release could be directly triggered or enhanced by PtdIns(4,5)P$_2$ (Kobayashi et al., 1989; Ogawa and Harafuji, 1989; Chu and Stefani, 1991; Ohizumi et al., 1999). Although no clear correlate was given as to how PtdIns(4,5)P$_2$ could act under physiological conditions, results emphasized that PtdIns(4,5)P$_2$ either would be active because it is present in the SR membrane, or could somehow be released from the transverse tubule to the SR membrane upon muscle stimulation (Chu and Stefani, 1991). Under our conditions, VSP activation depletes PtdIns(4,5)P$_2$ in the transverse tubule membrane, and the possibility that PtdIns(4,5)P$_2$ could rapidly shuttle from the transverse tubule to the SR terminal cisternae upon cell depolarization seems unlikely. Nevertheless, given the close apposition between the DHPR and RyR1, one could propose that PtdIns(4,5)P$_2$ may either interact with a cytoplasmic region of RyR1 that is close to the transverse tubule membrane, or sneak into the molecular interactions that make Cav.1 control RyR1 opening.

Cav.1 could be the potential target, as PtdIns(4,5)P$_2$ has been shown to regulate the activity of other voltage-gated Ca$^{2+}$ channels (e.g., Suh et al., 2010), potentially through a dual interaction with a fatty acid–binding site on a transmembrane part of the channel and a cytoplasmic part of the channel (see Suh et al., 2012). Our present results provide no indication that Cav.1 Ca$^{2+}$ channel activity is strongly affected by VSP activation. However, it could still be that depletion of transverse tubule PtdIns(4,5)P$_2$ affects Cav.1–RyR1 interaction in a subtle way that preserves the voltage-dependent Ca$^{2+}$ channel activity.

Alternatively, PtdIns(4,5)P$_2$ could also be thought to act as a docking target for another protein capable of enhancing the efficiency of depolarization-induced SR Ca$^{2+}$ release. For instance, annexin VI, which was initially presumed to modify the activity of the Ca$^{2+}$ release channel from the SR luminal side, was then shown to be attached to transverse tubule membrane in isolated triads, likely because of its PtdIns(4,5)P$_2$-binding properties (Barrientos and Hidalgo, 2002). Also dysferlin, a transverse tubule membrane protein present at triadic junctions presumably in association with the DHPR, was recently shown to contribute to Ca$^{2+}$ homeostasis (Kerr et al., 2013), and is also known to interact with PtdIns(4,5)P$_2$ (Therrien et al., 2009).

The modulation of Ca$^{2+}$ release by transverse tubule PtdIns(4,5)P$_2$ level may be relevant under particular physiological or pathological conditions. PtdIns(4,5)P$_2$ is a substrate for phospholipase C and for type 1 PtdIns-3 kinase, making it an inescapable target in several signaling cascades; there is thus the possibility that specific conditions of activation of either or both of these enzymes does modify the transverse tubule PtdIns(4,5)P$_2$ content so as to modulate Ca$^{2+}$ release. The plasma membrane level of PtdIns(4,5)P$_2$ was also shown to be increased by hyperosmolarity in several cell types including cardiac cells (Nasuhoglu et al., 2002), which may occur in skeletal muscle during high intensity exercise (Lindinger et al., 1992). The potential for alteration in phosphoinositide metabolism to trigger specific muscle diseases was demonstrated by the fact that deficiency in the phosphatidylinositol-phosphate Mtm1 is responsible for myotubular myopathy (Taylor et al., 2000). Interestingly, there is strong evidence that defective SR Ca$^{2+}$ release is primarily involved in this
disease (Al-Qusairi et al., 2009; Rodríguez et al., 2014). Collectively, our results demonstrate the potential offered by expression of VSPs in adult muscle fibers to investigate signaling mechanisms dependent on plasma membrane phosphoinositides and suggest that voltage-activated SR Ca\(^{2+}\) release is enhanced by the presence of PtdIns(4,5)P\(_2\) in the transverse tubule membrane.

We are grateful to Dr. Tamas Balla for providing us the PLC\(_{δ}\)PH-mRFP construct. We thank Ms. Megumi Kobahashi for generating the GFP-tagged Dr-VP construct; Thomas Loustau for performing early preliminary experiments; Jimmy Perrot for technical help; Bruno Allard for critical comments on the manuscript; and Bruno Allard, Pierre Charnet, and Norbert Weiss for helpful discussion.

This work was supported by grants from Centre National de la Recherche Scientifique and Université Lyon 1 to Centre de Génétique et de Physiologie Moléculaire et Cellulaire, and by a grant from Association Française contre les Myopathies to V. Jacquemond (AFM no. 15677).

The authors declare no competing financial interests.

Eduardo Ríos served as editor.

Submitted: 23 October 2014
Accepted: 5 March 2015

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Intramembrane charge movement in VSP-negative and VSP-positive fibers

Membrane currents were measured in response to 100-ms-long depolarizing pulses of increasing amplitude. The holding potential was set to 0 mV to annihilate or at least limit the contribution of currents caused by voltage-gated ion channels (including the DHPR voltage-sensing and Ca²⁺-conducting activities) that otherwise would have completely precluded detection of intramembrane charge movement at the large depolarizing levels necessary to activate the VSPs. Although we are aware that taking measurements from fibers held at 0 mV may somewhat negatively shift the voltage dependence of VSP charge as compared with a standard ~80-mV holding potential (see Villalba-Galea et al., 2008), there was hardly any alternative way this could be achieved in this preparation.

Fig. S1 (A–C) shows examples of membrane current traces, processed as described in Materials and methods to extract charge movement, from a VSP-negative fiber, a Ci-VSP–positive fiber, and a Dr-VSP–positive fiber, respectively. The inset in each panel shows the corresponding voltage dependence of the amount of on and off charge normalized to cell capacitance. Fig. S1 A illustrates the fact that VSP-negative fibers yielded small nonlinear transient currents at the onset and termination of the pulse. Similar transient changes were present in previously published records of membrane current from depolarized levels in muscle fibers (e.g., Fahlke and Rüdel, 1995; DiFranco et al., 2011). These currents were of opposite polarity from those anticipated from VSP function, and the amount of charge in the on component always exceeded the one in the off. These currents were not the result of erroneously subtraction of gating charge in the control pulses, as these were made positive to avoid contamination from charge 2 (Brum and Rios, 1987). The origin and properties of these currents were not further explored, but because they had to also be present in the VSP-expressing fibers, they contaminated, to some extent, detection of the VSP charge movement. Despite this limitation, Ci-VSP– and Dr-VSP–expressing fibers clearly yielded specific nonlinear currents, respectively positive and negative in terms of the onset and termination of the depolarizing pulses. Fig. S1 D shows the voltage dependence of the mean amount of off charge measured in VSP-negative fibers (n = 6), Dr-VSP–positive fibers (n = 4), and Ci-VSP–positive fibers (n = 5). For quantification, the off was preferred because of the lower amount of contaminating current inferred from measurements in VSP-negative fibers. The dependence of charge versus voltage was more positive and the maximum amount of charge was larger in Dr-VSP fibers than in Ci-VSP fibers. Fitting the voltage dependence of charge movement in each fiber with a Boltzmann function gave mean values for Qmax (maximal available charge), V0.5 (voltage of equal charge distribution), and k (steepness) of 19.3 ± 4.3 nC/µF, 59.6 ± 6.2 mV, and 15.7 ± 2.5 mV in Ci-VSP–expressing fibers and 85.4 ± 4.9 nC/µF, 89.4 ± 4.2 mV, and 15.6 ± 0.6 mV in Dr-VSP–expressing fibers, respectively. These results are consistent with the voltage-sensing domain of the VSPs being active in the transverse tubule membrane of the transfected muscle fibers. Interestingly, the voltage dependence of Ci-VSP and Dr-VSP gating currents found here is similar to the one reported previously in standard expression systems. For instance, the average mid-activation voltage for Ci-VSP and Dr-VSP was 59.6 and 89.4 mV in the muscle fibers as compared with either 62.9 and 94.3 mV (Hossain et al., 2008) or 55 and 100 mV (Falkenburger et al., 2010) in tsA201 cells, respectively. Furthermore, gating current kinetics were slower in fibers expressing Dr-VSP as compared with fibers expressing Ci-VSP, consistent with previously reported features of the VSPs in tsA201 cells (Hossain et al., 2008). Also interestingly similar was the more robust charge movement detected in Dr-VSP– than in Ci-VSP–expressing cells, by a factor of ~2 in the tsA201 cells (Falkenburger et al., 2010) and by a factor of ~4 in the muscle fibers. The codon usage index (CAI) in mammalian cells was found to be higher for Dr-VSP than for Ci-VSP mRNA (CAI = 0.78 vs. 0.69, calculated using mouse codon usage table: Puigbò et al., 2008), which may contribute to the more robust expression of Dr-VSP in mammalian cells. In terms of absolute density, assuming 1.5 charge moving per voltage sensor, the mean maximal amount of charge moved at depolarized voltages would correspond to ~800 and ~3,600 molecules of Ci-VSP and Dr-VSP per µm² of transverse tubule membrane. Although this is less than the corresponding levels reported in tsA201 cells (four and seven times, respectively; Falkenburger et al., 2010), it is within the order of magnitude or larger than the previously reported density of PtdIns(4,5)P2 in the transverse tubule membrane of skeletal muscle (435 molecules per µm²; Milting et al., 1994). Thus, it seems more than reasonable to anticipate that substantial depletion of the transverse tubule PtdIns(4,5)P2 pool does occur upon VSP activation in this system.
Estimation of the changes in transverse tubule membrane voltage from measurements of di-8-anepps fluorescence

In the silicone voltage-clamp condition, previous measurements with microelectrodes in the silicone-free fiber extremity established that in response to depolarizing or hyperpolarizing pulses of 20–40 mV the membrane voltage reached 90–95% of the command pulse value (Collet et al., 1999). In the present work, in response to large pulses to 100 or 120 mV, the membrane potential could not be expected to stay so close to the command voltage because of large outward potassium currents. To check for the actual membrane voltage reached, we measured the changes in the fluorescence of di-8-anepps in fibers voltage clamped under the same conditions as used in the VSP-expressing fibers. Di-8-anepps fluorescence transients in differentiated muscle fibers are known to arise mostly from the transverse tubule membrane and should thus provide a reliable estimate of the voltage changes experienced by the VSP.

Fig. S2 shows the results from these measurements. Fig. S2 (B and D) shows changes in membrane current and in di-8-anepps fluorescence recorded from a fiber stimulated by successive transient voltage-clamp pulses of 500-ms duration from −80 to −60, −40, −20, 0, 40, 80, and 120 mV (Fig. S2 A). Fig. S2 C shows the line-scan image collected in response to the pulse from −80 to 20 mV. As expected, depolarizing pulses produced a transient decrease in fluorescence, the amplitude of which increased with the pulse amplitude. The inset in Fig. S2 D presents the percent change in di-8-anepps fluorescence measured near the end of the pulse versus the command voltage. The line superimposed to the data points corresponds to the result from fitting a linear relationship to the first three data points (command voltage to −60, −40, and −20 mV for which little, if any, voltage-dependent calcium or potassium conductance was activated). The measured changes in di-8-anepps fluorescence for the largest pulses clearly escaped from this linear relationship. Assuming the transverse tubule membrane voltage being reasonably close to the command voltage for values between −80 and −20 mV, we used the linear relationship to estimate the actual membrane voltage reached at each depolarizing level. Fig. S2 E shows corresponding mean values for the estimated transverse tubule membrane voltage (estimated V) versus the command voltage from measurements taken in four fibers. According to this analysis, in response to the pulse to 120 mV, the actual membrane voltage

Figure S1. Intramembrane charge movement in VSP-expressing fibers. (A–C) Charge movement traces from a VSP-negative fiber, a Ci-VSP–positive fiber, and a Dr-VSP–positive fiber, respectively. In the three fibers, membrane voltage was stepped from a holding level of 0 mV to the values indicated in A. Insets show the corresponding voltage dependence of the amount of on and off charge. (D) Voltage dependence of the mean amount of off charge measured in VSP-negative fibers (n = 6), Dr-VSP–positive fibers (n = 4), and Ci-VSP–positive fibers (n = 5). Error bars represent ± SEM.
potential was close to 60 mV. This indicates that under these conditions, Ci-VSP was likely not fully activated, and thus the effect we see on Ca\(^{2+}\) release may actually be underestimated. This also likely contributes to the fact that Dr-VSP, which exhibits a more positive voltage dependence than Ci-VSP, appeared less effective in depressing Ca\(^{2+}\) release.

In a few fibers we also checked how fast the membrane gets depolarized by measuring di-8-anepps fluorescence transients in response to short (20-ms-long) depolarizing pulses using the spot detection mode of the microscope (32-kHz acquisition frequency). Fig. S2 F shows the time course of the command voltage (negatively scaled) and of the di-8-anepps response normalized to the same maximal amplitude. The command pulse was from \(-80\) to \(20\) V. The di-8-anepps trace corresponds to the average of 10 successive records. The superimposed red portions of traces show the result from fitting a single-exponential function to the decaying and rising phase of the di-8-anepps transient. From similar measurements and analysis taken in seven fibers, mean values for the time constant of decay and of rise of the fluorescence were \(0.67 \pm 0.33\) ms and \(0.77 \pm 0.4\) ms, respectively.

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**Figure S2.** Changes in transverse tubule membrane voltage measured with di-8-anepps in response to voltage-clamp depolarizing pulses. (A) Command voltage pulses applied to the fiber. (B) Corresponding changes in membrane current. (C) Line-scan image of di-8-anepps fluorescence recorded while the command pulse from \(-80\) to \(20\) mV was applied. (D) Time course of the relative changes in di-8-anepps fluorescence elicited by the pulses shown in A; fluorescence was integrated over the entire image width. In D, the inset shows the percent change in fluorescence measured near the end of the pulses versus the command voltage; a linear function was fitted through the first three data points (superimposed line). (E) Estimated membrane voltage versus applied command voltage (see text for details). Error bars represent ± SEM. (F) Normalized time course of change in di-8-anepps fluorescence recorded at high temporal resolution (noisy trace) in response to a 20-ms-long depolarizing pulse (clean trace). The red portions of lines correspond to the result from an exponential fit to the rising and decaying phase of the fluorescence transient.
DHPR Ca\textsuperscript{2+} current in VSP-negative and VSP-positive fibers

Membrane currents were measured in response to 1-s-long depolarizing pulses of increasing amplitude from a holding voltage of $-80$ mV. Fig. S3 A shows examples of membrane current traces corrected for the linear resistive component from a VSP-negative fiber, a Ci-VSP–positive fiber, and a Dr-VSP–positive fiber. Fig. S2 (B–D) shows mean values for the peak amplitude, time to peak, and time constant of decay of the current in VSP-negative, Ci-VSP–positive, and Dr-VSP–positive fibers. There was no statistically significant difference in any parameter between VSP-negative fibers and either Ci-VSP– or Dr-VSP–expressing fibers.

Figure S3. DHPR Ca\textsuperscript{2+} current in VSP-expressing fibers. (A) Ca\textsuperscript{2+} current traces from a VSP-negative fiber, a Ci-VSP–positive fiber, and a Dr-VSP–positive fiber in response to depolarizing pulses to $-20$, $-10$, $0$, $10$, and $20$ mV. Membrane current was acquired at a lower sampling rate in the VSP-negative fiber. (B–D) Mean voltage dependence of the peak amplitude, time to peak, and time constant of decay of the Ca\textsuperscript{2+} current in VSP-negative fibers ($n = 9$), Ci-VSP–positive fibers ($n = 4$), and Dr-VSP–positive fibers ($n = 6$). Error bars represent ± SEM.
REFERENCES


Video 1. Successive confocal images of the mRFP fluorescence from a skeletal muscle fiber expressing Ci-VSP and PLCβ₃PH-mRFP. The fiber was depolarized from −80 mV to the indicated levels. Frames were collected every 1.97 s and are displayed at a rate of four frames per second. Frame side size is 25.5 µm.

Video 2. Successive confocal images of the mRFP fluorescence from a skeletal muscle fiber expressing Ci-VSP and PLCβ₃PH-mRFP. The fiber was depolarized from −80 to 50 mV approximately between frame number 10 and frame number 12. Frames were collected every 2.35 s and are displayed at a rate of four frames per second. Frame side size is 51 µm.