Distinct α2 Na,K-ATPase membrane pools are differently involved in early skeletal muscle remodeling during disuse

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The Na,K-ATPase is essential for the contractile function of skeletal muscle, which expresses the α1 and α2 subunit isoforms of Na,K-ATPase. The α2 isozyme is predominant in adult skeletal muscles and makes a greater contribution in working compared with noncontracting muscles. Hindlimb suspension (HS) is a widely used model of muscle disuse that leads to progressive atrophy of postural skeletal muscles. This study examines the consequences of acute (6–12 h) HS on the functioning of the Na,K-ATPase α1 and α2 isoymes in rat soleus (disused) and diaphragm (contracting) muscles. Acute disuse dynamically and isoform-specifically regulates the electrogenic activity, protein, and mRNA content of Na,K-ATPase α2 isozyme in rat soleus muscle. Earlier disuse-induced remodeling events also include phospholemman phosphorylation as well as its increased abundance and association with α2 Na,K-ATPase. The loss of α2 Na,K-ATPase activity results in reduced electrogenic pump transport and depolarized resting membrane potential. The decreased α2 Na,K-ATPase activity is caused by a decrease in enzyme activity rather than by altered protein and mRNA content, localization in the sarcolemma, or functional interaction with the nicotinic acetylcholine receptors. The loss of extrajunctional α2 Na,K-ATPase activity depends strongly on muscle use, and even the increased protein and mRNA content as well as enhanced α2 Na,K-ATPase abundance at this membrane region after 12 h of HS cannot counteract this sustained inhibition. In contrast, additional factors may regulate the subset of junctional α2 Na,K-ATPase pool that is able to recover during HS. Notably, acute, low-intensity muscle workload restores functioning of both α2 Na,K-ATPase pools. These results demonstrate that the α2 Na,K-ATPase in rat skeletal muscle is dynamically and acutely regulated by muscle use and provide the first evidence that the junctional and extrajunctional pools of the α2 Na,K-ATPase are regulated differently.

INTRODUCTION

Investigations into the early molecular events that precede muscle atrophy are important for understanding the pathways involved in this disorder (Baldwin et al., 2013). Although the Na,K-ATPase is critically important for excitability, electrogenesis, and contractility of skeletal muscle (Sejersted and Sjøgaard, 2000; Clausen, 2013), its possible role in disuse-induced muscle atrophy is not known. The Na,K-ATPase is a P-type ATPase that catalyzes the active transport of K+ into and Na+ out of the cell, thereby maintaining the steep Na+ and K+ gradients that underlie the resting membrane potential (RMP) and electrical excitability. The Na,K-ATPase in skeletal muscle is composed of α-catalytic and β-glycoprotein subunits as well as a muscle-specific auxiliary FXYD1 subunit (phospholemman [PLM]), which modulates enzyme activity (Garty and Karlish, 2006; Geering, 2008). Four isoforms of the α-subunit are known to exist in tissues of vertebrates. It is generally accepted that the ubiquitous α1 isoform plays the main housekeeping role, whereas the other isoforms are expressed in a cell- and tissue-specific manner and possess additional regulatory functions that are still poorly understood (Blanco and Mercer, 1998; Geering, 2008; Krivoi, 2012).

The largest pool of Na,K-ATPase in a vertebrate’s body is contained in the skeletal muscles where the α1 and α2 isoforms of α subunit are expressed (Orlowski and Lingrel, 1988). The α2 isoform is expressed in high abundance in adult skeletal muscle compared with the
α1 isoform and comprises up to 87% of the total α subunit (Orlowski and Lingrel, 1988; He et al., 2001). However, its functional role and mechanisms of regulation remain incompletely understood (He et al., 2001; Radzyukevich et al., 2004, 2009, 2013; Krivoi et al., 2006; Heiny et al., 2010; Krivoi, 2012). Studies of the specific role of the α2 Na,K-ATPase isozone in skeletal muscle excitation, contraction, and fatigue have shown that this isozone is specifically regulated by muscle use and enables working muscles to maintain contraction and resist fatigue, revealing its vital role in movement (Radzyukevich et al., 2004, 2013; Heiny et al., 2010; DiFranco et al., 2015). Studies of the role of the cardiac glycoside-binding site on the Na,K-ATPase α2 isoform in skeletal muscle show that this site, using circulating endogenous digitalis-like ligands, plays a unique role in the dynamic regulation of active transport and adaptations to exercise (Radzyukevich et al., 2009).

PLM is one of the most abundant phosphoproteins in skeletal and cardiac muscle. It is a member of the FXYD family of small, single membrane–spanning proteins that act as tissue-specific regulators of the Na,K-ATPase. Phosphorylation of PLM by PKA and PKC alters the enzyme’s substrate affinity or turnover in a cell- and Na,K-ATPase isoform–specific manner (Geering, 2008; Bossuyt et al., 2009). In cardiac myocytes and skeletal muscle, PLM associates with both Na,K-ATPase α1 and α2 isoforms (Crambert et al., 2002; Reis et al., 2005; Rasmussen et al., 2008; Bossuyt et al., 2009; Chibalini et al., 2012).

Data obtained from different cells and tissues indicate that the Na,K-ATPase α2 isozone is the more regulated subunit compared with α1. Regulation of the α2 Na,K-ATPase is determined by its functional and molecular environment, by localization in specific cellular microdomains, and by its less stable integration into the lipid membrane compared with other Na,K-ATPase α isoforms (Song et al., 2006; Kapri-Pardes et al., 2011).

Skeletal muscle activity strongly regulates the content of Na,K-ATPase, and increased muscle activity differently regulates the α1 and α2 isoforms (Yuan et al., 2007; Kristensen et al., 2008; Murphy et al., 2008; Juel, 2009; Nordsborg et al., 2010; Clausen, 2013). These effects may involve exercise-induced regulation of PLM (Rasmussen et al., 2008; Juel, 2009); however, the mechanisms of this regulation remain to be elucidated. In addition, whether skeletal muscle disuse induces isoform-specific changes in Na,K-ATPase functioning has not been investigated in detail.

It is known that hindlimb suspension (HS), widely used as an animal model of disuse, leads to progressive atrophy of postural skeletal muscles (Morey-Holton et al., 2005; Shenkman and Nemirovskaya, 2008; Baldwin et al., 2013). After 3–7 d and more of HS, the rat soleus muscle undergoes several dramatic remodeling events, including a slow to fast shift in myosin heavy chain expression, changes in ion channel expression, calcium deregulation, cytoskeleton damage, etc. (Shenkman and Nemirovskaya, 2008; Baldwin et al., 2013; Pierno et al., 2013; Ogneva et al., 2014), and a decrease of the RMP (Desaphy et al., 2001; Pierno et al., 2002; Krivoi et al., 2008; Tyapkina et al., 2009). The decreased RMP was shown to result from lowered electrogenic Na,K-ATPase activity (Krivoi et al., 2008; Tyapkina et al., 2009); specifically, α2 isozone electrogenic activity decreases after 3 d of HS (Krivoi et al., 2008). Short-term (24–72 h) HS alters the Na,K-ATPase of rat soleus muscle in an isoform-specific manner and indicates that α2 Na,K-ATPase alterations precede disuse-induced muscle atrophy (Kravtsova et al., 2015). The effect of acute (hours) HS on the Na,K-ATPase isoforms is not known.

This study examines the consequences of acute HS on expression and function of the Na,K-ATPase α1 and α2 isoforms in rat soleus muscle. We subjected rats to HS for 6–12 h and analyzed its effect on the following parameters: the RMP of soleus fibers at different regions of the sarcolemma; the electrogenic transport activity of the α1 and α2 Na,K-ATPase, their protein and mRNA content; the extracellular level of acetylcholine (ACh); the plasma membrane localization of the nicotinic ACh receptors (nAChRs) and the α2 Na,K-ATPase and their functional interactions; and the phosphorylation status, abundance, and association of PLM with α2 Na,K-ATPase. In addition, we compared the characteristics of disused soleus muscle with the nonimpaired contracting diaphragm muscle of the same animals.

**MATERIALS AND METHODS**

**Animals**

Experiments were performed on male Wistar rats (180–230 g). Animals were housed in a temperature- and humidity-controlled room with food and water ad libitum. All procedures involving rats were performed in accordance with the recommendations for the Guide for the Care and Use of Laboratory Animals (http://www.nap.edu/books/0309053773/html/index.html). The protocol was approved by the Ethics Committee of St. Petersburg State University and the National Ministry of Health of the Russian Federation. The animals were subjected to HS individually in custom cages for 6 or 12 h, as described previously (Morey-Holton et al., 2005); control animals were not suspended. Soleus and diaphragm muscles were removed from eutanized animals. Freshly isolated muscles were used immediately for electrophysiological experiments, confocal microscopy imaging, or ACh assay. Some soleus muscles were quickly frozen in liquid nitrogen for later biochemical assays.

**Membrane potential recording**

The freshly isolated muscle with nerve stump was placed in a chamber and continuously perfused with a physiological solution containing (mM) 137 NaCl, 5 KCl, 2 CaCl₂, 2 MgCl₂, 24 NaHCO₃, 1 NaH₂PO₄, and 11 glucose, pH 7.4. The solution was continuously bubbled with 95% O₂ and 5% CO₂ and maintained at 24°C. The RMPs of muscle fibers were recorded from junctional and extra-junctional membrane regions using intracellular microelectrodes.
as described previously (Krivoi et al., 2006; Heiny et al., 2010). RMPs were recorded from 20–35 different fibers within each muscle, over a total recording time of ~5–10 min. The entire protocol was repeated in muscles from different animals.

In some experiments, a second set of RMP measurements were made before and immediately after the soleus muscle was stimulated to produce evoked contractions at 2 Hz for 5 min. Stimulation was achieved by delivering 0.1-ms isolated voltage pulses (Isotim A320; WPI) via two fine silver chloride wires and a suction electrode applied to nerve stump.

**Measurement of Na,K-ATPase electrogenic activity in intact muscle**

Na,K-ATPase transport activity was determined in intact muscle fibers by measuring the ouabain-sensitive change in RMP. This change is generated by electrogenic Na,K-ATPase transport and is a sensitive, real-time assay of Na,K-ATPase activity in intact skeletal muscle cells. The method is based on >100-fold difference in affinities of the rodent a1 and a2 Na,K-ATPase isoforms for ouabain. In rat skeletal muscle, 1 µM ouabain inhibits the a2 isoform without effect on the a1 isoform, whereas 500 µM ouabain completely inhibits both isoforms (Krivoi et al., 2003; Heiny et al., 2010; Chibalin et al., 2012). The electrogenic contribution of the a2 isoform was computed as the difference in mean RMP before and after 30-min incubation in 1 µM ouabain. The electrogenic contribution of the a1 isoform was estimated as the difference between the RMP in 1 µM ouabain and after 30-min incubation with 500 µM ouabain.

**Western blot and communoprecipitation assays**

Frozen isolated soleus muscles were homogenized in lysis buffer (mM: 10 Tris-HCl, 250 sucrose, 1 EDTA, and 1 EGTA, 2% Triton X-100, pH 7.4, and 1 tablet protease inhibitor [EMD Millipore] per 10 ml), homogenate was centrifuged at 10,000 g, and the supernatant was collected. The protein concentration was determined using a bicinchoninic acid protein assay kit (Thermo Fisher Scientific). Protein lysates were subsequently diluted into Laemmle buffer and heated at 56°C for 20 min.

A semiquantification of the a isoforms of Na,K-ATPase expression was performed as described previously (Matchkov et al., 2012). In brief, three 10% Tris-glycine gels were loaded with 10 µg of protein and electrotransferred after the separation onto nitrocellulose membranes. The membranes were blocked with 5% nonfat dry milk in PBS-T (mM: 137 NaCl, 2.7 KCl, 8.2 NaHPO₄, and 1.8 KH₂PO₄ and 0.5% vol/vol Tween 20 at pH 7.4). The membranes were incubated overnight at 5°C with primary antibodies in PBS-T (either a1 isoform [1:2,000; Santa Cruz Biotechnology, Inc.] or a2 isoform [1:2,000; EMD Millipore] or pan-actin [1:1,000; Cell Signaling Technology]). After washing, the membranes were incubated for 1 h with horseradish peroxidase–conjugated secondary antibody (1:4,000; Dako). The bound antibody was detected by an enhanced chemiluminescence kit (ECL; GE Healthcare). Detected protein was quantified as a ratio to pan-actin intensity using ImageJ software (National Institutes of Health).

To analyze signaling pathways, equal amounts of protein from the same samples (15 µg) were separated on precast Criterion SDS-PAGE gels of various percentages (Bio-Rad Laboratories) and transferred to PVDF membranes (Immobilon; EMD Millipore). Equal loading of protein on gels was ensured using Ponceau staining. Membranes were blocked in 7.5% milk in TBS-T for 1 h and incubated overnight with a primary antibody at 4°C. Then, the membranes were washed and incubated with the appropriate HRP–conjugated secondary antibody (Bio-Rad Laboratories) in 5% milk for 1 h at room temperature. Proteins were visualized using enhanced chemiluminescence Western blotting detection reagents from GE Healthcare. Optical density of the bands was quantified using the Quantity One imaging system (Bio-Rad Laboratories). Antibodies against PLM were from Proteintech; phospho-PLM Ser⁶⁸ and phospho-PLM Ser⁷⁰ antibodies were from Abnova.

**Comunoprecipitation assays**

Comunoprecipitation assays were performed as described previously (Heiny et al., 2010). In brief, muscles were solubilized with lysis buffer (157 mM NaCl, 2.7 mM KCl, 1 mM MgCl₂, 20 mM Tris, pH 8.0, 1% Triton X-100, 10% [vol/vol] glycerol, 10 mM NaF, 0.5 mM NaVO₄, 5 µg/ml leupeptin, 0.2 mM phenylmethylsulfonyl fluoride, 5 µg/ml aprotinin, and 1 µM microcystin). Immunoprecipitation was performed in 1 ml of lysis buffer containing 500 µg of protein using a primary antibody to the a2 isoform of the Na,K-ATPase antibody (EMD Millipore) followed by affinity purification using protein A–agarose beads (Invitrogen). After incubation with protein A–agarose beads for 1 h at room temperature, the immuno complex was washed in lysis buffer followed by PBS. The protein samples were probed by Western blot with primary antibodies against Na,K-ATPase a2 subunit (clone McB2; provided by K. Sweadner, Massachusetts Central Hospital, Boston, MA) and PLM (Proteintech). The proteins were visualized by ECL and quantified by densitometry.

**Quantitative polymerase chain reaction (PCR)**

Isolated soleus muscle segments were disrupted in Tissuelyser (QIAGEN). RNA isolation was performed with the Mini kit (QIAGEN) in a Qiacube robotic workstation for automated purification of RNA (QIAGEN). PCR was performed to assess the expression of specific RNAs. The reaction was executed with reverse transcription III (Invitrogen) and SUPERase (Ambion) for deactivation of RNase and DNase. The standard primer sets for quantitative PCR analyses for a1 and a2 isoforms of the Na,K-ATPase were obtained from Applied Biosystems. Quantitative PCR was performed on an MX3000P (Agilent Technologies) using TaqMan probe (FAM technology). Gene expression was normalized to GAPDH and transferrin receptor (Ct value) levels and presented by a ΔCt value. Comparison of gene expression was derived by subtracting control ΔCt (an averaged ΔCt for the muscles which were not exposed to HS) from sample ΔCt, producing ΔΔCt. Relative gene expression was calculated as 1/(2⁴ΔΔCt), thereby standardizing to control muscle.

**Confocal microscopy and membrane localization**

Ouabain at 1 µM selectively inhibits the rodent a2 Na,K-ATPase without effect on the a1 isoform, as shown previously (Krivoi et al., 2003; Chibalin et al., 2012). For selective imaging of the Na,K-ATPase a2 isoform, a freshly isolated soleus muscle was incubated for 15 min with physiological saline containing fluorescent-labeled specific ligands of the Na,K-ATPase (BODIPY–conjugated ouabain, 1 µM) and the nAChR (rhodamine-conjugated α-bungarotoxin, 1 µM). Superficial regions of the muscle were imaged with a 40×, 1.3 NA objective using a TCS SPS confocal system (Leica) configured for concurrent viewing of rhodamine and BODIPY fluorescence, as described previously (Heiny et al., 2010; Radzyukevich et al., 2013). Fluorescence was estimated as mean fluorescence intensity in arbitrary units (a.u.) at different sarcolemma regions using Image Pro software (Media Cybernetics). Analysis of junctional fluorescence was performed in the region defined by α-bungarotoxin staining. Extrajunctional fluorescence was calculated for an area (~200 µm²) of muscle membrane outside of the α-bungarotoxin–positive region.

**ACh assay**

Fluorescence images were acquired using a CX41 microscope (Olympus) equipped with FluorLED fluorescence illuminators (Fraen) and charge-coupled device camera DP72 (Olympus). Analysis was performed using Image Pro software (Media Cybernetics).

The level of ACh released in neuromuscular preparations with native acetylcholinesterase (AChE) was estimated optically using

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Ouabain was obtained from Sigma-Aldrich. Rhodamine-conjugated α-bungarotoxin was from Biotium, Inc., and BODIPY-conjugated ouabain was from Invitrogen. Nicotine (\((-\)nicotine hydrogen tartrate) and other chemicals were from Sigma-Aldrich.

Statistics
Data are given as the mean ± SEM. Statistical significance of the difference between means was evaluated using a Student’s t test (ORIGIN 6.1 software) and one-way ANOVA (ORIGIN Pro 8 software).

RESULTS
Acute HS dynamically alters the RMP of rat muscles
In control soleus muscles, the mean RMPs of junctional (end-plate) and extrajunctional membrane regions were \(-76.6 ± 0.4\) mV and \(-73.7 ± 0.4\) mV, respectively (significant difference of \(-2.9 ± 0.6\) mV, \(P < 0.01\)). A similar local hyperpolarization of junctional membrane was observed in control diaphragm muscles (Fig. 1, A and D).

The more negative RMP of junctional compared with...
extrajunctional membrane regions of the same muscle is consistent with previous studies (Nikolsky et al., 1994; Heiny et al., 2010) and is attributed to enhanced electrogenic activity of the Na,K-ATPase α2 isozyme at the neuromuscular junction (NMJ) of rodents (Heiny et al., 2010). Nanomolar concentrations of ACh resulting from nonquantal release stimulate the enzyme through an interaction between the nAChR and the Na,K-ATPase α2 isozyme (Krivoi et al., 2006; Heiny et al., 2010; Chibalin et al., 2012). A stable, reciprocal modulation between these proteins was further confirmed in an insect nervous system (Bao et al., 2015). Presumably, the nAChR in a desensitized conformation with high apparent affinity for agonist interacts with the Na,K-ATPase to stimulate active transport, and this effect does not require ion flow through open nAChRs (Heiny et al., 2010). The junctional membrane hyperpolarization might also involve ATP-sensitive K⁺ channels opening in response to local Na,K-ATPase activation and ATP depletion within a diffusion-restricted submembrane space (Kabakov, 1998; Zhu et al., 2014). In accordance with the length constant of a skeletal muscle cell, the hyperpolarization disappeared within ~2 mm from visually identified terminal branches of the nerve.

After 6 h of HS, the mean RMPs of both junctional and extrajunctional membranes of soleus fibers depolarized to approximately −70 mV and were similar at all regions. The mean RMP in the junctional region was −70.3 ± 0.4 mV, representing a depolarization of 6.3 ± 0.6 mV (P < 0.01) compared with control (Fig. 1 A). After 12 h of HS, the mean RMP of the junctional but not extrajunctional membrane regions returned to control values (−75.6 ± 0.5 mV). In this case, the junctional membrane was again hyperpolarized by −5.7 ± 0.7 mV compared with extrajunctional regions as in control (Fig. 1 A).

In diaphragm muscles, which continuously contract during HS, the junctional membrane depolarized to a similar extent as the disused soleus muscles after 6 h of HS. However, conversely to soleus muscles, there was no recovery of mean junctional RMP after 12 h of HS. Additionally, in contrast to soleus, the mean RMP of extrajunctional membrane regions of diaphragm muscles did not change after 6 or 12 h of HS (Fig. 1, A and D).

The RMPs of all soleus and diaphragm muscle groups showed a Gaussian distribution (Fig. 1, B, C, E, and F). Therefore, the changes produced by HS represent a simple shift of the mean RMP without change in normal distribution.

HS alters the RMP by modulating the electrogenic transport activity of the α2 Na,K-ATPase isozyme

The transport activity of the Na,K-ATPase α1 and α2 isozymes was determined by measuring the ouabain-sensitive change in RMP (see Materials and methods). Fig. 2 shows the mean RMPs measured before and after exposure to 1 and 500 µM ouabain. In the junctional region of control soleus muscles, total electrogenic activity by the Na,K-ATPase contributes −14.3 ± 0.8 mV to the RMP. Of this, the α2 isozyme generates −5.5 ± 0.8 mV and the α1 isozyme generates −8.8 ± 0.8 mV. Therefore, the α2 and α1 isozymes contribute 38% and 62%, respectively, of basal Na⁺/K⁺ transport at the junctional membrane of rat soleus muscle (Figs. 2 A and 3 A).

HS alters these contributions in an isoform-specific manner. After 6 h of HS, the ouabain-sensitive electrogenic potential contributed by α2 isozyme decreased dramatically to only −0.2 ± 0.7 mV (P < 0.01), whereas the electrogenic potential contributed by α1 isozyme remained unchanged at −8.5 ± 0.6 mV (P < 0.01; Fig. 3 A). Therefore, the HS-induced membrane depolarization is almost entirely caused by a specific decrease in α2 isozyme activity. After 12 h of HS, α2 isozyme electrogenic activity at the NMJ recovered to control value without changes in α1 isozyme activity (Fig. 3 A). This suggests that restoration of the mean RMP at the junctional membrane during HS involves α1 isozyme activity, which is consistent with previous studies (Nikolsky et al., 1994; Heiny et al., 2010) and is attributed to enhanced electrogenic activity of the Na,K-ATPase α2 isozyme at the neuromuscular junction (NMJ) of rodents (Heiny et al., 2010). Nanomolar concentrations of ACh resulting from nonquantal release stimulate the enzyme through an interaction between the nAChR and the Na,K-ATPase α2 isozyme (Krivoi et al., 2006; Heiny et al., 2010; Chibalin et al., 2012). A stable, reciprocal modulation between these proteins was further confirmed in an insect nervous system (Bao et al., 2015). Presumably, the nAChR in a desensitized conformation with high apparent affinity for agonist interacts with the Na,K-ATPase to stimulate active transport, and this effect does not require ion flow through open nAChRs (Heiny et al., 2010). The junctional membrane hyperpolarization might also involve ATP-sensitive K⁺ channels opening in response to local Na,K-ATPase activation and ATP depletion within a diffusion-restricted submembrane space (Kabakov, 1998; Zhu et al., 2014). In accordance with the length constant of a skeletal muscle cell, the hyperpolarization disappeared within ~2 mm from visually identified terminal branches of the nerve.

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membrane after 12 h HS results from a specific increase in α2 isozyme activity.

In extrajunctional membrane regions of the soleus muscle, the activity of α1 isozyme did not change during 6 or 12 h of HS (Fig. 3 B). In contrast, α2 isozyme activity decreased from $-3.2 \pm 0.7$ mV in control to $-0.9 \pm 0.7$ mV (P < 0.01) after 6 h of HS. No recovery was observed, and after 12 h of HS the electrogenic activity of α2 isozyme was only $-1.3 \pm 0.6$ mV (Fig. 3 B). Therefore, in extrajunctional membrane regions, HS of up to 12 h produces only depolarization without recovery of the RMP. Overall, electrogenic activity by the α1 isozyme is similar in junctional and extrajunctional membrane regions and is not changed by HS, whereas α2 isozyme activity is dynamically modulated.

The question arises: could changes in the RMP after HS be caused by a mechanism other than a change in the Na,K-ATPase electrogenic activity? For example, more prolonged HS of 3 d or more up-regulates voltage-dependent Na⁺ and ClC-1 chloride channels (Desaphy et al., 2001; Piermo et al., 2002) and down-regulates the ATP-sensitive K⁺ channels (Tricarico et al., 2010) in the rat soleus muscle. These permeability changes are expected to alter the RMP independent of any change in electrogenic pump potential. This possibility is unlikely caused by the finding that both control and HS-treated muscles establish the same RMP (approximately $-62$ mV) when the Na,K-ATPase electrogenic contribution is completely blocked with 500 µM ouabain (Fig. 2, A and B). Similar ouabain-induced RMP changes were observed in diaphragm muscles (not depicted). This result confirms that HS changes the RMP via the α2 electrogenic pump contribution rather than by a change in ion permeability.

In diaphragm muscles, which continuously contract during HS, the electrogenic activity of α1 isozyme did not change after 6 h of HS in both regions of sarcolemma. The electrogenic activity of α2 isozyme at the junctional membrane decreased to the same extent as in soleus muscle after 6 h of HS, whereas α2 isozyme activity in extrajunctional membrane (as well as RMP; Fig. 1 D) was not changed (Fig. 3, C and D). Again, conversely to soleus muscles, there was no recovery of junctional α2 isozyme electrogenic activity after 12 h of HS; the electrogenic activity of the extrajunctional α2 isozyme pool was not change after both 6 and 12 h of HS (Fig. 3, C and D).

Therefore, acute HS preferentially depolarizes the RMPs of skeletal muscle fibers through corresponding isof orm-specific changes in the electrogenic transport activity of the α2 Na,K-ATPase, and the junctional and extrajunctional pools of α2 Na,K-ATPase are regulated differently.

Low-intensity muscle workload specifically restores the electrogenic activity of α2 Na,K-ATPase

In some experiments, RMP measurements were repeated on HS-suspended soleus muscles before and immediately after the muscle was stimulated to produce evoked contractions at 2 Hz for 5 min (see Materials and methods). This protocol hyperpolarizes the RMP by stimulating the Na,K-ATPase (Hicks and McComas, 1989), and extracellular K⁺ accumulation might specifically stimulate the α2 Na,K-ATPase (DiFranco et al., 2015). This
low-intensity workload transiently hyperpolarized both junctional and extrajunctional sarcolemma regions of soleus muscles after 6 h of HS (Fig. 4). The hyperpolarization was inhibited in a dose-dependent manner by 100 nM to 1 µM ouabain (Fig. 4), indicating that it arises from ouabain-sensitive α2 Na,K-ATPase electrogenic activity. This result provides further evidence that α2 Na,K-ATPase activity is specifically responsive to muscle use.

It should be noted that, if the excitation-related Na,K-ATPase activity causes ATP depletion in a local subsarcolemmal space (Kabakov, 1998; Zhu et al., 2014), ATP-sensitive K+ channels will open and contribute an additional component to the measured hyperpolarization. In any case, these data indicate that a low-intensity workload can specifically restore the activity of the α2 Na,K-ATPase isozyme in hindlimb-suspended muscles. This result provides further evidence that the activity of α2 Na,K-ATPase depends strongly on muscle use and that it is retained in the sarcolemma during 6 h of HS (see also Fig. 9).

**Figure 4.** Repetitive stimulation of rat soleus muscle after 6 h of HS specifically restores the electrogenic transport activity of the α2 Na,K-ATPase isozyme. (A and B) RMPs were measured in the junctional (A) and extrajunctional (B) membrane regions before and immediately after the soleus muscles were stimulated at 2 Hz for 5 min (see Materials and methods). The experiments were performed without ouabain (circles, six muscles) and in the presence of 100 nM (triangles, eight muscles) or 1 µM (squares, six muscles) ouabain (30-min preincubation). ***, P < 0.001 compared with corresponding value in the absence of ouabain. Error bars indicate SEM.

**Figure 5.** 12 h of HS specifically alters α2 Na,K-ATPase protein and mRNA content. (A and B) Relative Na,K-ATPase α1 and α2 protein (A) and mRNA content (B) in whole homogenates from the rat soleus muscles of control rats (Con) and after 6 and 12 h of HS. In A, the expression levels of α1 and α2 proteins were semiquantified by normalization of band intensities to the band intensity of pan-actin made from the same lysate. Top panels show representative immunoblots. In A and B, data were normalized to the mean level of expression under control conditions. Columns show mean data from 8–10 (A) and 5–16 (B) different muscle samples. **, P < 0.01 compared with control. Error bars indicate SEM.
Na,K-ATPase α2 isozyme activity at extrajunctional membrane regions (Fig. 3 B). In sum, these data suggest that the decrease in α2 Na,K-ATPase activity in the soleus muscle is caused by an acute regulation of enzyme activity by muscle use, rather than by altered protein or mRNA content.

Role of PLM in the early disuse-induced remodeling events
To investigate the molecular mechanisms that regulate Na,K-ATPase α2 activity in response to muscle disuse, we investigated the expression and phosphorylation state of proteins known to regulate Na,K-ATPase activity. PLM, a partner protein for the Na,K-ATPase, plays an important role in its regulation (for reviews see Geering [2008] and Pavlovic et al. [2013]).

In our study, PLM abundance increased 1.4-fold (P < 0.05) after 6 h of HS. Notably, the phosphorylation of PLM on Ser⁶³ and Ser⁶⁸ also increased significantly after 6 h of HS, increasing 2.75-fold (P < 0.01) and 1.6-fold (P < 0.01), respectively. These effects were transient, and after 12 h of HS, PLM abundance and phosphorylation tended to return toward control levels (Fig. 6, A and B). The association of PLM with the α2 Na,K-ATPase measured as coimmunoprecipitation also was strong and tended to increase after 6 h of HS (P = 0.11; Fig. 6, C and D).

These data provide evidence to suggest that 6 h of HS might affect the Na,K-ATPase α2 by a phosphorylation-dependent mechanism and by increased PLM abundance and its association with α2 Na,K-ATPase. We cannot exclude the possibility that a subpopulation of the Na,K-ATPase α2 may be activated by increased phosphorylation of PLM. However, as a net effect, we observe α2 pump inhibition.

HS does not alter the functional interaction of nAChR with α2 Na,K-ATPase
To confirm that α2 Na,K-ATPase remains in the membrane and is functional during acute HS, we tested whether the Na,K-ATPase α2 isozyme is able to be stimulated by nanomolar concentrations of nAChR agonists. This effect is based on the functional interaction between the nAChRs and the Na,K-ATPase (Krivoi et al., 2006; Heiny et al., 2010). Upon exposure of rat soleus muscles to 100 nM nicotine, a small but significant (P < 0.01) depolarization was detected in both junctional and extrajunctional membrane regions. The depolarization, expected if 100 nM nicotine initially opens a small number of nAChRs, was followed by sustained hyperpolarization (Fig. 7 A).

After 6 h of HS, the initial RMPs of both sarcolemma regions depolarized to approximately −70 mV; however, Na,K-ATPase activity in both regions was able to be stimulated further by nicotine, indicating the continued presence of Na,K-ATPase in both junctional and extrajunctional membrane (Fig. 7 B). The nicotine-induced hyperpolarization was inhibited by 50 or 100 nM ouabain (Fig. 7 C), consistent with previous data attributing this hyperpolarization to specific stimulation of ouabain-sensitive Na,K-ATPase α2 isozyme activity (Krivoi et al., 2003; Heiny et al., 2010). These data indicate that the Na,K-ATPase α2 isozyme, even after being inhibited by 6 h of HS, remains capable of dynamically increasing its transport activity in response to nanomolar nAChR agonist.

HS does not alter the regulation of α2 Na,K-ATPase
electrogenic transport by extracellular ACh
It is possible that HS might lower the level of endogenous nonquantal ACh release and thereby selectively decrease

Figure 6. HS alters PLM abundance, phosphorylation, and its association with α2 Na,K-ATPase. (A and B) PLM abundance and phosphorylation at Ser⁶³ and Ser⁶⁸. (C and D) PLM coimmunoprecipitates with the Na,K-ATPase α2 subunit. Bar graphs show the mean density from 10 (A and B) and 4 (C and D) measurements of different muscle samples. Representative immunoblots are shown. *, P < 0.05; **, P < 0.01 compared with corresponding control. Error bars indicate SEM.
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Experiments as well as experiments with the addition of exogenous AChE (not depicted) demonstrate that choline fluorescence decreases by at most 25–35% after 6 h of HS (Fig. 8). This result indicates that 6 h of HS induces a small decrease in extracellular ACh levels in soleus muscles. In contrast, choline fluorescence in diaphragm muscles increases by the same small amount after 6 h of HS (Fig. 8). These opposite changes in ACh levels suggest that the significant decrease in α2 Na,K-ATPase transport activity (Fig. 3) induced in both soleus and diaphragm muscles after 6 h HS is not explained by changes in extracellular ACh levels.

Investigation of α2 Na,K-ATPase localization in the sarcolemma

It is possible that HS may alter the localization of α2 Na,K-ATPase in the sarcolemma and thereby alter its electrogenic contribution in different membrane regions. We investigated this possibility by imaging the NMJ of intact soleus muscles dual labeled with fluorescent, specific ligands of the Na,K-ATPase (BODIPY-conjugated ouabain, 1 µM) and the nAChR (rhodamine-conjugated αbungarotoxin). In control muscles, the fluorescent ouabain signal overlaps with the α-bungarotoxin signal at the end-plate regions, confirming that the α2 Na,K-ATPase and the nAChR colocalize at the postsynaptic NMJ (Fig. 9 A, a–c), as reported previously (Heiny et al., 2010). 6 and 12 h of HS did not affect the colocalization between these proteins (Fig. 9 A, d–f and g–i) and did not alter the fluorescence signal from either α2 Na,K-ATPase or nAChRs (Fig. 9 B). These observations confirm that α2 Na,K-ATPase distribution at the NMJ does not change after both 6 and 12 h of HS, times when electrogenic activity by the α2 pump is completely lost and then recovered, respectively (Fig. 3 A). The stable colocalization of the nAChRs with the α2 Na,K-ATPase after 6 h of HS is also expected from the finding that the functional interaction between these proteins remains (see above, Fig. 7).

Figure 7. HS does not alter the functional interaction between nAChR and α2 Na,K-ATPase. (A–C) Changes in membrane potential induced by 100 nM nicotine in rat soleus muscle fibers in control (A), after 6 h of HS (B), and in the presence of ouabain (C). In A and B, junctional membrane (open circles), extrajunctional membrane (closed circles); horizontal bars indicate the periods when nicotine was present in the perfusate. In C, muscles were preincubated with the indicated concentration of ouabain for 30 min before nicotine addition. RMPs were recorded from extrajunctional membrane regions. Changes in RMP were calculated as the difference between the potential measured before and after 60 min of nicotine action. **, P < 0.01 compared with corresponding value in the absence (0 nM) of ouabain. Error bars indicate SEM.

Figure 8. Extracellular ACh levels in control and after 6 h of HS. Choline fluorescence (a.u.) after 15-min incubation of soleus and diaphragm muscles from control rats (white bars, four muscles) and rats after 6 h of HS (gray bars, four muscles). *, P < 0.05 compared with the corresponding control. The fluorescence was compared with the Ach standard curve to estimate the amount of ACh (µM) accumulated in 0.4 ml of bathing solution normalized per gram of muscle tissue (right y axis). Error bars indicate SEM.
In addition to the NMJ, the $\alpha_2$ Na,K-ATPase isozyme is also present on extrajunctional sarcolemma and transverse tubule membranes (Williams et al., 2001). Consistent with this expectation, the fluorescent ouabain signal is also detected on extrajunctional sarcolemma in the transverse tubules, evident as double rows of label with a repeat pattern of two per sarcomere. This pattern is expected from the dual transverse-tubule openings at the A-I junctions of mammalian muscle (Fig. 9 A, j), consistent with previous studies (Heiny et al., 2010; Radzyukevich et al., 2013). As with the junctional membrane, 6 h of HS did not alter the extrajunctional localization (Fig. 9 A, k) or fluorescence signal (Fig. 9 B) from the Na,K-ATPase $\alpha_2$ isozyme. However, after 12 h of HS, the fluorescence from the $\alpha_2$ Na,K-ATPase increased by 22% ($P < 0.05$; Fig. 9 B), suggesting the increased abundance in the extrajunctional sarcolemma. This finding corresponds well with enhanced $\alpha_2$ Na,K-ATPase protein and mRNA content after 12 h of HS (Fig. 5). Nevertheless, no recovery of extrajunctional $\alpha_2$ pump activity was observed at this time point (Fig. 3 B). Collectively, these data suggest that $\alpha_2$ Na,K-ATPase is retained in the soleus muscle sarcolemma during 6–12 h of HS, and disuse-induced changes of $\alpha_2$ pump activity cannot be explained by altered membrane localization.

**DISCUSSION**

The novelty of this study is that acute disuse dramatically and specifically alters the activity, mRNA, and protein content of the Na,K-ATPase $\alpha_2$ isoform, and this represents an early event in the progression to muscle atrophy. The decreased $\alpha_2$ Na,K-ATPase activity depolarizes the RMP by reducing the negative potential contributed by electrogenic pump transport, and this may occur in part via a PLM-dependent regulatory mechanism. Intriguingly, junctional and extrajunctional pools of the $\alpha_2$ Na,K-ATPase are regulated differently.

The Na,K-ATPase is obligatory for excitability, electrogensis, and the contractility of skeletal muscles (Sejersted and Sjøgaard, 2000; Clausen, 2013). The skeletal muscle pool of Na,K-ATPase demonstrates a high level of plasticity in response to a variety of physiological conditions. Its transport activity is modulated over a wide dynamic range by several acute interventions. These have been reviewed extensively and include membrane excitation, muscle contraction, circulating hormones, neurotransmitters, and endogenous inhibitors. In addition, longer-term interventions such as exercise training or chronic hormonal status can modulate the protein content of Na,K-ATPase (Clausen, 2013). The wide regulatory range of Na,K-ATPase activity and content allows skeletal muscles to match Na+/K+ transport capacity to the varying demands of resting and contracting muscle and to adapt to chronic changes in levels of inactivity, activity, or training.

Although adaptations of Na,K-ATPase content and activity in response to increased physiological loading are well documented (Yuan et al., 2007; Kristensen et al., 2008; Murphy et al., 2008; Juel, 2009; Nordsborg et al., 2010; Benziane et al., 2012; Clausen, 2013), the effects of physical inactivity induced by functional unloading and other conditions (Leivseth et al., 1992; Krivoi et al., 2008; Boon et al., 2012; Kravtsova et al., 2015;...
Perry et al., 2015) are relatively few in numbers. The molecular mechanisms underlying the changes have not been investigated.

Adult skeletal muscle coexpresses α1 and α2 isoforms of the Na,K-ATPase catalytic and transport α subunit (Orlowski and Lingrel, 1988). Most prior studies of the regulation of Na,K-ATPase in skeletal muscle by acute interventions have measured total Na,K-ATPase activity or content contributed by the combined α1 and α2 isoform pools. However, the α1 and α2 isoforms in skeletal muscle have distinct distributions with respect to content and membrane localization, suggesting that they play distinct physiological roles. The α1 isoform comprises up to 40% of total Na,K-ATPase α subunit and is expressed only on the outer plasma membrane. The α2 isoyme comprises 60–80% of total Na,K-ATPase content (Orlowski and Lingrel, 1988; He et al., 2001), and the majority of α2 isoyme is expressed in the interior transverse tubule membranes, with smaller pools localized to the postsynaptic NMJ and surface caveolae (Williams et al., 2001; Heiny et al., 2010). In resting, noncontracting skeletal muscles, the α2 isoyme operates far below its maximum transport capacity. Although the α1 isoyme provides up to 75% of the Na+/K+ transport needed to maintain basal ion gradients and the resting potential, the α2 Na,K-ATPase contributes only 25% of basal Na+/K+ transport (Krivoi et al., 2003; Chibalina et al., 2012). Because of the large size of the α2 Na,K-ATPase pool, even small changes in specific α2 isoyme activity are expected to produce large changes in total Na+/K+ transport capacity.

Several recent studies suggest that the α2 Na,K-ATPase pool provides a reserve transport capacity that can be activated in response to acute changes in muscle use, to meet the increased demands of contracting muscles for active Na+/K+ transport. The activity of the α2 pool at the NMJ increases rapidly during periods of nerve activity, through an interaction between the ACh-bound nAChR and the Na,K-ATPase α2 isoyme (Krivoi et al., 2003, 2006; Heiny et al., 2010). The resulting hyperpolarization primes the muscle junctional membrane to be more responsive to nerve input during periods of increased muscle use. The extrajunctional pool of Na,K-ATPase α2 is also stimulated by this mechanism, to a lesser extent.

The extrajunctional pool of α2 isoyme, presented in the surface caveolae and transverse tubules, plays an important role in clearing the excitation-related increases in extracellular K+ and intracellular Na+ that accompany action potential excitation. Studies of mice with a targeted KO of α2 isoyme in the skeletal muscles indicate that stimulation of α2 isoyme activity during muscle use is absolutely required for maintaining contractility and preventing fatigue in working muscles (Radzyukevich et al., 2013; DiFranco et al., 2015).

This study examined whether the Na,K-ATPase α1 and α2 isoforms in skeletal muscle are differentially regulated by acute decreases in muscle use. Acute muscle disuse induced by 6 h of HS dramatically reduced the Na,K-ATPase α2 transport activity of resting soleus muscles. Decreased α2 Na,K-ATPase activity is caused by a decrease in enzyme activity rather than by altered protein and mRNA content or localization in the sarcolemma. In addition, HS does not alter α2 Na,K-ATPase colocalization and functional interaction with the nAChRs.

Longer periods of HS up to 12 h selectively up-regulate α2 isoyme protein and mRNA content. It was shown that decreased Na,K-ATPase activity in skeletal muscle at fatigue is reciprocally correlated with increased α2 mRNA expression, suggesting a possible signal transduction role for depressed Na,K-ATPase activity on α isoyme gene expression (Petersen et al., 2005). The increased α2 mRNA expression may be a compensatory response to preserve muscle function. However, even the increased α2 Na,K-ATPase protein content and enhanced membrane abundance after 12 h of HS cannot counteract the sustained inhibition of α2 isoyme activity at extrajunctional membrane regions.

Notably, acute HS did not alter the activity and content of the α1 Na,K-ATPase isoyme. This finding is consistent with the emerging consensus that the α1 isoyme in muscle, as in other tissues, plays the major role in maintaining basal ion gradients, osmotic balance, and the resting potential, and it further supports the idea that the Na,K-ATPase α2 isoyme in skeletal muscle is the more regulated isoyme that can respond to changes in muscle use.

HS is expected to induce systemic changes in the animal, in addition to muscle-specific changes in the inactive hindlimb muscles. Some studies indicate that animals show an initial, transient stress response to HS (Thomason and Booth, 1990). By comparing α2 Na,K-ATPase regulation in the inactive soleus muscle with the continuously active diaphragm muscle from the same animal, we were able to study the role of muscle inactivity per se on α2 Na,K-ATPase regulation. The decrease in α2 Na,K-ATPase activity on extrajunctional membranes, where the majority of α2 pump is localized, occurred only in the inactive soleus muscle. An interesting result was that the α2 activity in the junctional membranes decreased for both diaphragm and soleus muscles during 6 h of HS. However, conversely to soleus, there was no recovery of junctional α2 isoyme activity in diaphragm muscle after 12 h of HS. This finding indicates that the junctional and extrajunctional pools of α2 isoyme are regulated differently. The extrajunctional pool of the α2 isoyme is regulated by disuse, whereas the small subset of α2 Na,K-ATPase at the junctional membrane is regulated by disuse as well as by additional systemic factors (possibly circulating stress factors) related to HS. Importantly, application of a low-intensity workload is able to restore the electrogenic transport activity of both junctional and extrajunctional
pools of α2 Na,K-ATPase, providing further evidence that regulation of Na,K-ATPase α2 activity depends strongly on muscle use. The molecular mechanisms that differentially regulate the α2 Na,K-ATPase in different membrane compartments remain to be elucidated.

The molecular mechanisms by which disuse downregulates the activity of α2 Na,K-ATPase are not known. This study investigated whether PLM plays a role in this regulation. Other studies have shown that PLM acts as a brake on the Na,K-ATPase, whereas phosphorylation removes this brake and increases pump activity by increasing the affinity of intracellular Na’ sites (reviewed in Geering [2008] and Pavlovic et al. [2013]). In skeletal muscle, at least 30% of α1 and α2 Na,K-ATPase isoforms are associated with PLM (Rasmussen et al., 2008). The increased PLM abundance and increased association with the α2 Na,K-ATPase after 6 h of HS suggest that inhibition by PLM may underlie the acute, total inhibition of α2 Na,K-ATPase electrogenic activity. In contrast, we detected an increase in PLM phosphorylation, which is expected to stimulate the Na,K-ATPase. PLM phosphorylation can be induced by multiple signaling pathways and receptors, including stress-related β-adrenergic receptors acting through PKA. Short-term HS may alter PLM regulation of Na,K-ATPase by more than one mechanism, with the dominant effect toward the reduced activity.

Other factors related to muscle disuse may be also involved in the inhibition of α2 Na,K-ATPase functional activity during acute HS. Reduced EMG and neurogram activity after HS (Ohira et al., 2002; De-Doncker et al., 2005) is expected to reduce PKC activity. In fact, PKC activity is known to decrease after short HS (Pierno et al., 2007), and this in turn could alter the phosphorylation state of the Na,K-ATPase α or PLM subunits (Walaas et al., 1994; Mahmoud and Cornelius, 2002). Additional studies of the regulation of Na,K-ATPase activity, in particular the less-studied α2 isoform, will be needed to interpret these results.

**Physiological implications**

Other studies also suggest that the α2 Na,K-ATPase plays a special role in adaptations to skeletal muscle disuse. Chronic disuse resulting from spinal cord injury (Boon et al., 2012) or knee injury (Perry et al., 2015) significantly decreases the α2 Na,K-ATPase content in skeletal muscles. The disuse-induced decrease in Na,K-ATPase α2 electrogenic activity and steady membrane depolarization is expected to decrease muscle excitability and contractility. Maintaining the necessary level of skeletal muscle RMP is essential for many physiological processes, including ion homeostasis and normal action potential generation. The disuse-induced steady depolarization of junctional membrane is expected to inactivate Na’ channels and lower the safety factor for neuromuscular transmission by increasing the threshold for generation of the muscle action potentials (Wood and Slater, 2001). Depolarization of extrajunctional membrane is expected to decrease excitability and impair action potential generation and voltage-dependent excitation-contraction coupling. Also, loss in Na,K-ATPase α2 activity should result in an additional excitation-related K’ load in the T-tubules in working muscles (DiFrancesco et al., 2015). These effects are in a direction to exaggerate muscle weakness under conditions in which the safety factor for excitation is already impaired. Disuse-induced changes in the Na,K-ATPase are also expected to alter the function of Na’-dependent transporters and other processes that depend on the Na’ gradient established by the Na,K-ATPase. Our data provide the first evidence that such remodeling during HS starts early and that the α2 Na,K-ATPase is specifically altered. Considering the unique role of the α2 Na,K-ATPase isozyme in excitation, contraction, and adaptation to exercise (Radzyukevich et al., 2004, 2009, 2013; Krivoi, 2012), disuse-induced α2 Na,K-ATPase alterations might be an important player in adaptations of skeletal muscle to altered use.

We are very grateful to St. Petersburg State University Research Center for Molecular and Cell Technologies and personally to Nikolai A. Kostin for assistance with confocal microscopy experiments. This study was supported for I.I. Krivoi by Russian Foundation for Basic Research (RFBR) grant #13-04-00973 and St. Petersburg State University research grants #1.50.1621.2013 and #1.38.231.2014; for V.V. Matchkov by the Danish Research Council grant #09063499 and the Novo Nordisk Foundation grant #NRF14OC0012731; for A.V. Chibalina by Swedish Research Council grant #K2013-55X-14191-12-3, the Strategic Research Program in Diabetes at Karolinska Institutet, and the Novo Nordisk Foundation grant #10559; for A.M. Petrov by RFBR grant #14-04-00984; for A.L. Zefirov by RFBR grant #14-04-01232; and for J.A. Heiny by National Institutes of Health grant #1 R01 AR063710.

The authors declare no competing financial interests.

Author contributions: V.V. Kravtsova, A.M. Petrov, A.N. Vasiliev, E.V. Bouzinova, and B. Benziane performed all experiments, data collection, and analysis. V.V. Matchkov, A.V. Chibalina, and A.L. Zefirov were involved in the interpretation of data. I.I. Krivoi and J.A. Heiny designed and wrote the manuscript. The project was directed by I.I. Krivoi. All authors approved the final version of the manuscript for publication.

Eduardo Rios served as editor.

Submitted: 10 August 2015
Accepted: 22 December 2015

**REFERENCES**


