Proteasome inhibitor (MG132) rescues Na\textsubscript{v}1.5 protein content and the cardiac sodium current in dystrophin-deficient mdx\textsuperscript{5cv} mice

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The cardiac voltage-gated sodium channel, Na\textsubscript{v}1.5, plays a central role in cardiac excitability and impulse propagation and associates with the dystrophin multiprotein complex at the lateral membrane of cardiomyocytes. It was previously shown that Na\textsubscript{v}1.5 protein content and the sodium current (I\textsubscript{Na}) were both decreased in cardiomyocytes of dystrophin-deficient mdx\textsuperscript{5cv} mice. In this study, wild-type and mdx\textsuperscript{5cv} mice were treated for 7 days with the proteasome inhibitor MG132 (10 μg/Kg/24 h) using implanted osmotic mini pumps. MG132 rescued both the total amount of Na\textsubscript{v}1.5 protein and I\textsubscript{Na} but, unlike in previous studies, the novo expression of dystrophin was not observed in skeletal or cardiac muscle. This study suggests that the reduced expression of Na\textsubscript{v}1.5 in dystrophin-deficient cells is dependent on proteasomal degradation.

Keywords: sodium channels, dystrophin, proteasome, proteasome inhibitors, MG132, electrophysiology
MATERIALS AND METHODS

ANIMALS
Wild-type (WT) C57BL/6 mice (Janvier, Le Genest St Isle, France), and C57BL/6 Ros-5Cv (mdx<sup>5cv</sup>) mice (Jackson laboratories, Bar Harbort, USA) were raised at the department of pharmacology of the University of Lausanne. Male mice aged 12–16 weeks were used in this study. All animal procedures were performed in accordance with Swiss and cantonal laws.

MINI PUMPS
Osmotic mini pumps (ALZET model 1007D, Alzet Osmotic Pump Company, Cupertino, USA) were implanted in the anterior border region of the mice. Pumps were filled up with either a MG132 solution or with the vehicle alone (0.9% NaCl) according to the ALZET filling procedure. MG132 (C2211, SIGMA, Buchs, Switzerland) was delivered at a dose of 10 mg/kg/24 h. Two millimolars MG132 aliquot were added to dimethylsulfoxide (Merck, Dammstadt, Germany), before being further diluted to the appropriate concentration in 0.9% NaCl.

MICE VENTRICULAR MYOCYTE ISOLATION
Seven days after implantation of the osmotic pump, the mice were heparinized with 100 μl of heparin (Liquemin 5000 IU/ml, Roche, Basel, Switzerland). They were then euthanized with an intraperitoneal injection of pentobarbital. The hearts were excised, rinsed in Krebs solution, mounted on a Langendorff apparatus and subjected to collagenase retroperfusion. The procedure for mice ventricular myocyte isolation was previously described in detail (Gavillet et al., 2006). Approximately 10% of the isolated myocytes were plated on a laminin coated dish and used for patch clamp experiments; the remaining myocytes were frozen in pellet form. The frozen pellets were subsequently used for mRNA or protein extraction.

PROTEIN EXTRACTION
The gastrocnemius muscles were removed, washed with ice cold PBS1X and frozen in liquid nitrogen. Frozen myocytes and skeletal muscles were transferred into lysis buffer (50 mM TRIS pH 7.5, of 1%, and solubilization occurred by rotating for 1 h at 4°C). The lysate was centrifuged at 13,000 g for 15 min at 4°C. The protein concentration of each lysate was measured in triplicate by the method of the SDS-PAGE with equivalent amounts of total protein, the normalized current or conductance, and the voltage-dependence of steady-state activation and inactivation, measured during a current voltage protocol. To quantify the protein concentration of each lysate was measured in triplicate by the method of the SDS-PAGE with equivalent amounts of total protein, the normalized current or conductance was measured during a current voltage protocol. To quantify the voltage-dependence of steady-state activation and inactivation, data from individual cells were fitted with the Boltzmann relationship:

\[ \frac{\exp\left[\frac{V_m - V_1/2}{k}\right]}{1 + \exp\left[\frac{V_m - V_1/2}{k}\right]} \]

where \(V_m\) is the membrane potential, \(V_1/2\) is the voltage at which half of the available channels are inactivated, \(k\) is the slope factor, and \(\exp\) is the membrane potential.

STATISTICAL ANALYSES
Data were represented as mean values ± SEM. Two-tailed Student’s t-test was used to compare means. Statistical significance was set at \(P < 0.05\).

RESULTS

THE PROTEASOME INHIBITOR MG132 RESCUES NA<sub>1.5</sub> PROTEIN LEVELS AND THE SODIUM CURRENT IN mdx<sup>5cv</sup> MICE
The cardiac voltage-gated sodium channel, Na<sub>1.5</sub>, is part of the DMC in mouse cardiomyocytes (Gavillet et al., 2006). The Na<sub>1.5</sub> gene is expressed in the heart and is essential for the generation of action potentials. Na<sub>1.5</sub> is a key regulator of cardiac conduction and excitation-contraction coupling. The expression and function of Na<sub>1.5</sub> are altered in several cardiac diseases, including myocardial infarction and cardiomyopathy.

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protein content and the $I_{\text{Na}}$ were both decreased in mdx$^{5cv}$ mice, in which dystrophin is not expressed (Gavillet et al., 2006). In addition, it was shown that the sodium channel could be ubiquitinated by ubiquitin protein ligases of the Nedd4 family, thereby regulating the density of the channel at the cell membrane (van Bemmelen et al., 2004). In order to determine whether the ubiquitin proteasome system is implicated in the diminution of the sodium channel in the cardiomyocytes of dystrophin-deficient mice, control and mdx$^{5cv}$ mice were treated with the proteasome inhibitor MG132. Osmotic mini pumps were implanted subcutaneously and delivered MG132 at a dose of 10 μg/kg/24 h over a 7-day period. Western blot experiments were performed using cardiomyocyte lysates of mdx$^{57}$ and control mice, both treated with either MG132 or saline solution (0.9% NaCl). The protein content of Na$_{1.5}$ in the cardiomyocytes was quantified by digital density measurements of several Western blots, such as the one represented in Figure 1A. The total amount of Na$_{1.5}$ protein was decreased by 49 ± 3% in the ventricular myocytes of mdx$^{5cv}$ mice treated with the saline solution, as compared to control mice (Figures 1A,B). The MG132 treatment increased the protein level of Na$_{1.5}$ in mdx$^{5cv}$ cardiomyocytes to a level similar to that in control mice (Figures 1A,B). The proteasome inhibitor had no effect on the Na$_{1.5}$ protein content in control mice (Figures 1A,B). Finally, Na$_{1.5}$ mRNA quantification was performed using real time quantitative PCR. No significant difference of the Na$_{1.5}$ transcript between mdx$^{57}$ and control mice was observed in either treatment (Figure 1C).

The $I_{\text{Na}}$ was decreased by 29 ± 6% in mdx$^{5cv}$ mice, as compared to that in the controls (Figures 2A,B). The proteasome inhibitor had a strong effect on the $I_{\text{Na}}$ of mdx$^{5cv}$ cardiac cells, increasing the current to a level similar to that found in control mice (Figures 2A,B). The effect of MG132 treatment on $I_{\text{Na}}$ was restricted to an increase in the current density, since neither the voltage-dependence of activation nor the steady state of inactivation were affected by the treatment (Figure 2C).

MG132 TREATMENT DOES NOT RESCUE DYSTROPHIN EXPRESSION IN SKELETAL OR CARDIAC MUSCLES

Bonuccelli et al. (2003) previously reported that the systemic treatment with 10 μg/Kg/24 h of MG132 rescued the expression of...
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FIGURE 2 | Effects of MG132 treatment on the sodium current properties and mRNA level. (A) Current density-voltage relationship of $I_{\text{Na}}$ in control and mdx$^{5cv}$ mice treated with MG132 or 0.9% NaCl, as indicated. The protocol is indicated in inset. (B) Bar graph quantifying the amounts of sodium current in control and mdx$^{5cv}$ ventricular myocytes. Four cells were patched for each mouse and the number of mice used for quantification is indicated in the bars. The “normalized current” represents the maximum current density recorded at a given voltage (−25 mV). (C) Steady-state activation and inactivation curves. The protocol is indicated in inset. The number of mice used for quantification is indicated in the bars. Results are expressed as normalized mean signal intensity. *$P < 0.05$, n.s. not significant.

the dystrophin protein in skeletal muscle of the “original” mdx mouse strain. In the present study, Western blots of mdx$^{5cv}$ gastrocnemial muscle lysates were performed in order to determine whether dystrophin is expressed in skeletal muscle upon treatment with MG132. The dystrophin antibody used for the Western blots was directed against the actin binding site in the N-terminus. The mdx$^{5cv}$ mouse strain has a mutation in exon 10, which leads to a premature stop codon in the full-length transcript (Im et al., 1996). One can assume that if a shorter dystrophin form had been produced in mdx$^{5cv}$ muscles upon MG132 treatment, it may have been detected. As expected, dystrophin expression was undetectable in cardiac and skeletal muscle lysates of mdx$^{5cv}$ mice treated with 0.9% NaCl (Figures 3A,B). However, contrary to that described with the “original” mdx mice, MG132 treatment did not rescue the dystrophin expression in mdx$^{5cv}$ skeletal muscle or cardiomyocytes (Figures 3A,B).

Nedd4-2 AND THE β1-SUBUNIT mRNA AMOUNTS ARE NOT MODIFIED BY MG132 TREATMENT

Nav$_{1.5}$ was shown to be regulated by the ubiquitin ligase protein Nedd4-2, which is expressed in the heart (van Bemmelen
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FIGURE 3 | Dystrophin is not expressed in skeletal muscle and in cardiomyocytes of mdx5cv mice treated with MG132. Western blots of mouse ventricular myocytes (A) and gastrocnemius muscle (B) lysates of control and mdx5cv mice treated with MG132 or 0.9% NaCl, as indicated.

FIGURE 4 | MG132 treatment does not modify the mRNA expression level of SCN1B and Nedd4-2 genes. Bar graph representing the amounts of SCN1B (A) and Nedd4-2 (B) mRNA in control and mdx5cv ventricular myocytes, analyzed by quantitative real time PCR (Taqman®) as described in the Material and Methods. The number of mice used for quantification is indicated in the bars. Results are expressed as normalized mean signal intensity. n.s. not significant.

et al., 2004; Rougier et al., 2005). The β-subunits of Na+,1.5 were shown to modulate channel activity (Yu et al., 2005). In addition, the β1 -subunit of Na+,1.5 (encoded by the gene SCN1B) was described to be down-regulated in the skeletal muscle of DMD patients (Haslett et al., 2002). In order to determine whether these proteins play a role in the regulation of Na+,1.5 in mdx5cv mice treated with MG132 or 0.9% NaCl, real time quantitative PCR experiments were performed to quantify the relative amounts of mRNA. Figures 4A,B illustrate that there are no differences between the different tested conditions, suggesting that these proteins are not likely involved in the modulation of Na+,1.5 upon MG132 treatment.

DISCUSSION

Treatment of “original” dystrophin-deficient mice with the proteasome inhibitor MG132 was shown to rescue dystrophin expression in their skeletal muscle (Bonuccelli et al., 2003). The authors did not, however, investigate the effect of MG132 on cardiac muscle (Bonuccelli et al., 2003). In the mdx5cv mouse strain, the Na+,1.5 protein content is decreased by ∼50% and the $I_{Na}$ by ∼30% (Gavillet et al., 2006). Studies using heterologous expression systems have demonstrated that ubiquitylation of Na+,1.5 could trigger its internalization and decrease $I_{Na}$ (van Bemmel et al., 2004). In the present work, control and mdx5cv mice were treated with MG132 in order to investigate the implications of the ubiquitin proteasome system on the regulation of Na+,1.5 in cardiac cells. The main findings of this study are: (1) the proteasome inhibitor MG132 rescues the sodium channel Na+,1.5 and $I_{Na}$ in mdx5cv cardiomyocytes, and (2) MG132 does not rescue the dystrophin expression in either cardiac or skeletal muscle in mdx5cv mice.

The proteasome is a proteolytic complex which rapidly degrades ubiquitylated proteins (Rock et al., 1994). MG132 is a molecule which reversibly blocks protein degradation by the proteasome (Rock et al., 1994). The results of the present work suggest that the decrease of Na+,1.5 observed in mdx5cv mice could be either directly or indirectly mediated by the proteasome. It is more likely that the proteasome is indirectly implicated in the regulation of Na+,1.5 since membrane proteins are primarily degraded by the lysosomal apparatus in eukaryotic cells, whereas the proteasome is involved in the proteolysis of cytosolic proteins (Lee and Goldberg, 1998). The activity of endocytic proteins is regulated by ubiquitin...
signals and the proteasome could control the degradation of these ubiquitylated proteins (Longa et al., 2002). Components of the endocytic machinery that undergo ubiquitylation are, however, primarily monoubiquitylated and the proteasome recognizes polyubiquitylated proteins. It has been suggested that endocytosed proteins might be transiently polyubiquitylated and degraded by the proteasome (Salghetti et al., 2001). Altogether, these results suggest that the proteasome indirectly regulates Na+ 1.5. Additional experiments using endocytosis or lysosome inhibitors should be carried out to help identify the proteolytic pathways involved in the degradation of Na+ 1.5.

Unlike Bonacelli et al. (2003), this study did not use the “original” mdx mouse strain which carries a premature stop codon in exon 23, since this strain was shown to have revertant fibers due to exon skipping events (Danko et al., 1992). This study used the mdx5cv mouse strain which carries an A to T mutation in the middle of exon 10 that produces a new splice donor site and results in a premature stop codon in full-length transcripts (Im et al., 1996). MG132 treatment of mdx5cv mice did not rescue dystrophin expression in skeletal or cardiac muscle. The different effects of MG132 treatment on the two mouse strains could be due to the nature of the dystrophin mutations. The mutation on the dystrophin gene of mdx5cv mice may produce an unstable transcript which is not translated, whereas the “original” mdx strain may produce an unstable protein that accumulates upon MG132 treatment. This interpretation is supported by the study of Assere et al. (2006) on the DMC composition of DMD and BMD muscle explants following in vitro treatment with 20 μM MG132. Only some of the DMD and BMD explants showed signs of DMC rescue after treatment, probably due to the nature of the dystrophin mutations.

In conclusion, it was observed that the proteasome inhibitor MG132 rescued the total amount of Na+ 1.5 protein and the Its, in cardiomyocytes, but did not rescue dystrophin expression in dystrophin-deficient mdx5cv mice. Moreover these results suggest that the proteasomal pathway is implicated in the degradation of Na+ 1.5 channel in dystrophinopathies. We have yet to determine if the proteasome is directly or indirectly involved in the degradation of polyubiquitylated Na+ 1.5 channel or if it regulates the endocytic machinery which controls the density of the sodium channel at the plasma membrane. Additional experiments on the mechanisms of Na+ 1.5 channel degradation and regulation in WT and dystrophin-deficient cardiac cells are needed to better understand the pathways involved in the maintenance of the Na+ 1.5 channel in specific pools.

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