Cu/Zn superoxide dismutase typical for familial amyotrophic lateral sclerosis increases the vulnerability of mitochondria and perturbed Ca\(^{2+}\) homeostasis in SOD1\(^{G93A}\) mice

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Running title: Cu/Zn superoxide dismutase of fALS in SOD1<sup>G93A</sup> mice

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Abbreviations: ALS, amyotrophic lateral sclerosis; AM, acetoxy methyl ester; CCD, charge cooled device; DMSO, dimethyl sulfoxide; ER, endoplasmic reticulum; F, fluorescence; fALS, familial amyotrophic lateral sclerosis; FCCP, carbonyl cyanide p-(trifluoromethoxy) phenylhydrazone; HMNs, hypoglossal motoneurons; hALS, human amyotrophic lateral sclerosis; Rhod123, rhodamine 123; ROI, regions of interest; ROS, reactive oxygen species; RyR, ryanodine receptor; SEM, standard error of the mean (SEM); SERCA, sarco-endoplasmic reticulum Ca<sup>2+</sup> ATPase; SOD1, Cu/Zn superoxide dismutase 1; TPP<sup>+</sup>, tetraphenylphosphonium salt; [Ca<sup>2+</sup>]<sub>i</sub>, cytosolic calcium; [Ca<sup>2+</sup>]<sub>mito</sub>, mitochondrial calcium; WKS, weeks; WT, wild-type; Δψ<sub>m</sub>, mitochondrial membrane potential.
Abstract

Amyotrophic lateral sclerosis (ALS) is a fatal neurodegenerative disorder characterized by the selective loss of defined motoneuron populations in the brainstem and spinal cord. Though low cytosolic calcium ([Ca^{2+}]_i) buffering and a strong interaction between metabolic mechanisms and [Ca^{2+}]_i have been associated with selective motoneuron vulnerability, the underlying cellular mechanisms are barely understood. To elucidate the underlying molecular events, we utilized rapid charge cooled device imaging to evaluate Ca^{2+} signaling and metabolic signatures in the brainstem slices of SOD1^{G93A} mice, the mouse model of human ALS, at 8-9 and 14-15 weeks of age, corresponding to the pre-symptomatic and symptomatic stages of motor dysfunction, respectively, and compared the results with corresponding age-matched wild-type littermates. We also monitored the mitochondrial membrane potential (Δψ_m) of brainstem motoneurons, a valuable tool for characterizing the metabolic signature of intrinsic energy profiles and considered to be a good experimental measure for monitoring energy metabolism in cells. We found that different pharmacological interventions substantially disrupt Δψ_m in SOD1^{G93A} motoneurons during the symptomatic stage. Furthermore, we investigated the impact of impaired mitochondrial mechanisms on [Ca^{2+}]_i regulation by using the membrane-permeable indicator fura-AM. Taken together, the results indicate that mitochondrial disruptions are critical elements of SOD1^{G93A}-mediated motoneuron degeneration in which selective motoneuron vulnerability results from a synergistic accumulation of risk factors, including the disruption of electrochemical potential, low Ca^{2+} buffering, and strong mitochondrial control of [Ca^{2+}]_i. The stabilization of mitochondria-related signal cascades may represent a useful strategy for clinical neuroprotection in ALS.
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Introduction

Amyotrophic lateral sclerosis (ALS) is an adult-onset disease characterized by the degeneration of vulnerable motoneuron populations leading to paralysis and death within 5 years (Rowland and Schneider, 2001). The disease is subclassified epidemiologically as sporadic, familial, and endemic forms (Shibata, 2001), with the majority being sporadic. However, approximately 10% of cases are familial ALS (fALS) and approximately 20% of fALS cases are caused by inherited dominant mutations in the Cu/Zn-superoxide dismutase gene (SOD1; Rosen et al., 1993). Although the process of motoneuron degeneration in both the sporadic and familial forms is still not fully understood, researchers generally agree that there are cell-specific features impairing the mitochondrial uptake of Ca\(^{2+}\) and a low Ca\(^{2+}\) binding protein content modulating physiological and pathophysiological processes, which may render motoneurons selectively vulnerable to degeneration in ALS (Alexianu et al., 1994; Lips and Keller, 1998; Van Den Bosch et al., 2002). The loss of mitochondrial membrane potential (ΔΨ\(_{m}\); Carri et al., 1997), excitotoxic stimulation of AMPA/kainate receptors (Carriedo et al., 2000), and age-related motoneuron injury (Beal, 2002; Menzies et al., 2002) may contribute to ALS pathogenesis.

Mitochondrial Ca\(^{2+}\) uptake and buffering has been associated with multiple physiological processes in motoneurons, including rhythmic activity, synaptic plasticity, and regeneration after axonal damage, and has been closely linked to the regulation of electrical excitability and neurodegeneration (Bergmann and Keller, 2004; Von Lewinsky and Keller, 2005; Spitzer, 2006). Excessively elevated mitochondrial Ca\(^{2+}\) ([Ca\(^{2+}\)]\(_{mito}\)) results in cell death by ATP depletion (Gunter and Gunter, 1994), depolarization of the ΔΨ\(_{m}\) (Schinder et al., 1996), and subsequent generation of reactive oxygen species (ROS; Dykens et al., 1994). There is evidence indicating that mutated SOD1 targets mitochondria leading to structural alterations,
such as mitochondrial swelling and vacuolization, in affected motoneurons (Wong et al., 1995; Kong and Xu, 1998; Menzies et al., 2002b). It has also been shown that SOD1G93A inhibits complex II and IV of the mitochondrial electron transport chain leading to depolarization of the ΔΨm and likely play a causal role in SOD1-induced motoneuron death (Mattiazzi et al., 2002). Alterations in mitochondrial electron transport, which frequently includes a decrease in complex IV, have also been found in various patients with sporadic ALS (Swerdlow et al., 1998; Borthwick et al., 1999; Vielhaber et al., 2000; Wiedemann et al., 2002).

Over the past decade, increased understanding of local interactions between Ca2+ and its target signaling pathways has emerged. Therefore, understanding the roles of Ca2+ signaling and mitochondria-mediated toxicity in ALS is crucial and of great importance. Several studies indicate that motoneuron death induced by SOD1G93A involves the disruption of Ca2+ homeostasis; however, the underlying mechanisms are still not understood. An attractive way to investigate motoneuron function under physiological and pathophysiological conditions is to perform whole cell patch clamp recordings and simultaneously monitor cytosolic signaling pathways by fluorescence microscopy (Ladewig and Keller, 2000). Previous motoneuron studies have been done on primary cultures (Carriedo et al., 2000), isolated motor nerve terminals (David et al., 2003), or by patch-clamping motoneurons in acute mouse brain slices (Ladewig et al., 2003; Bergmann and Keller, 2004). Unfortunately, the application of the patch clamp technique to brainstem slices from adult mice is exceptionally difficult; therefore, it is important to also use alternative technical approaches. Previous attempts to use membrane-permeable forms of fluorometric calcium and membrane potential indicators to load neuron populations have worked well only in cultures or slices of neonatal brain tissue. In the current study we attempt to introduce a robust approach for loading membrane-
permeable fluorescent indicator dyes in adult brain slices and utilize pharmacological and fluorimetric approaches to investigate the consequences of mitochondrial inhibition on \([Ca^{2+}]_i\) and \(\Delta \psi_m\) in the hypoglossal motoneurons (HMNs) of adult brainstem slices. The preparation of brainstem slices from adult wild-type (WT) and corresponding SOD1\(^{G93A}\) mice is particularly valuable because it preserves motoneurons in their physiological environment in a functionally intact state and provides a way to study disease progression in a natural environment.

**Materials and methods**

*Transgenic mice and PCR-genotyping*

TgN (SOD1-G93A) 1Gur (Fast Line) mice were obtained from The Jackson Laboratory (Bar Harbour, Maine, USA). The Tg strain can be considered a model for human amyotrophic lateral sclerosis (hALS). The mice carry a variation of the human SOD1 gene, in which position 93 glycine is replaced by alanine (Gurney et al., 1994). These mice develop paralysis in the limbs and die at 4-5 months of age. This results from the continuously expanding loss of MNs from the brainstem and spinal cord. After the onset of symptoms life expectancy varies from 4 to 6 weeks. Animal experiment procedures were approved and carried out in accordance with the guidelines of the ethics committee of the Medical Faculty of the University of Göttingen and met with national standards for humane care of animals. Animals were kept under a 12 h dark and light period, at \(21 \pm 2\) °C and \(55 \pm 10\) % relative humidity, were fed a standard Sniff diet (Sniff, Soest, Germany) ad libitum, and had free access to water.
PCR genotyping procedure was adapted from Hoyaux et al., 2000. The Tg male mice were bred with female B6SJL F1-hybrids obtained from the Jackson Laboratory (Bar Harbour, Maine, USA) and from Charles River (Germany). Tg mice were identified using polymerase chain reaction. Within the first few days after birth (1-5 days), a piece of the mouse tail was dissected and 300µl diagnostic buffer (20mM Tris HCl at pH: 8.4, 50mM KCl, 0.45% NP40, 0.45% Tween 20) and 5µl Proteinase K (20mg/ml) were added. After stirring, the process of digestion was supported by incubation for 2 hours at 55°C and denaturing for 10 min at 95°C. The homogenate was then put on ice for 10 min and centrifuged at 1000xg for 1min. For amplification DNA (1µl) from the digestion process, Aqua dest (47.5µl), Taq PCR Master mix kit (50µl, Qiagen, Hilden, Germany) and special primers (0.4µl for each primer, ARK Scientific) were used to identify two genes: first the human SOD1 gene on exon 4 consisting of 236bp (primer1: oIMR114:5’-CGC GAC TAA CAA TCA AAG TGA-3’ and primer 2: oIMR113:5’-CAT CAG CCC TAA TCC ATC TGA-3’) and second the endogenous murine Il2 gene consisting of 324bp (primer 3: oIMR042:5’-CTA GGC CAC AGA ATT GAA AGA TCT-3’ and primer oIMR043:5’-GTA GGT GGA AAT TCT AGC ATC ATC -3’). The Il2-gene is used as a control for DNA amplification. The transgene carriers will amplify both genes; the wild-type samples will amplify only Il2-gene. The amplification runs 35 cycles including 4 min at 94°C for initial denaturation, 1 min at 92°C, 1 min at 60°C and 1 min at 72°C. Finally the temperature is held at 72°C for 5 min and then cooled to 10°C. 10µl PCR-product and 5µl 6X loading buffer (MBI Fermantas, Vilnus, Lithuania) were run on a 2% agarose gel (80ml tray with 7µl ethidium bromide dye) along with a 100bp DNA ladder (MBI Fermantas, Vilnus, Lithuania) to estimate the size of the products.

Preparation of acute adult mouse brain stem slices and identification of hypoglossal motoneurons
Hypoglossal motoneurons (Nucleus hypoglossus; XII) areas were visually identified by their location proximity to the fourth ventricle while cutting the brainstem transversely (Fig. 1). *In-vitro* brain stem slice preparations were obtained from adult (8-9 and 14-15 weeks) WT/SOD1<sup>G93A</sup> mice. Animals were anesthetized with diethyl ether vapor until the paw withdrawal reflex disappeared and then decapitated; brains were removed and subsequently cooled in 4°C cold artificial cerebrospinal fluid (aCSF). Transverse slices of the brainstem were cut with a thickness of ~200 µm using a vibroslicer (Leika VT 1000S, Göttingen, Germany) according to a method described previously (Ladewig and Keller, 2000). To achieve maximum oxygen supply aCSF (in mM: 118 NaCl, 3 KCl, 1 MgCl<sub>2</sub>, 25 NaHCO<sub>3</sub>, 1 NaH<sub>2</sub>PO<sub>4</sub>, 1.5 CaCl<sub>2</sub>, 20 glucose; pH 7.4; 320 mOsm) was continuously bubbled with carbogen (95% O<sub>2</sub>, 5% CO<sub>2</sub>). An essential requirement for simultaneous microfluorometric measurements was the preservation of neurons close to the slice surface in a functionally intact state. This was achieved by minimizing mechanical disturbances of tissue during slice preparations, performing isolation of slices at low temperatures (4°C) and optimising metabolic conditions by maximum oxygen supply. After slicing, slices were maintained at room temperature (RT, 20-23°C) for 30 min to allow recovering prior to dye loading. If not indicated otherwise, experiments were carried out at RT.

**CCD camera imaging**

Measurements of intracellular Ca<sup>2+</sup> concentrations and mitochondrial membrane potential were performed using a modified version of the CCD camera system (TILL Photonics, Planegg, Germany) as previously described (Lips and Keller, 1999; Ladewig and Keller, 2000). Briefly, a computer-controlled monochromator based on a galvanometric scanner
(Polychrome II, TILL Photonics, Martinsried, Germany) was connected to an upright microscope (Axioskope, Fa. Zeiss, Göttingen, Germany) via quartz fiber optics and a minimum number of optical components for maximum fluorescence excitation (objective Achromplan W 63x, 0.9W) was employed. Fluorescence was detected by a 12 bit CCD camera (PCO, Germany), binning of which was set to 4x4, sampling rates varied between 3 and 13 Hz. [Ca\textsuperscript{2+}]\textsubscript{i} changes in defined “regions of interest” (ROIs) drawn over the soma of motoneurons were monitored using a PC running TILL Vision Software V3.3 (TILL Photonics, Martinsried, Germany). The emitted light was directed to a dichroic mirror with mid reflection depending on the fluorescent dye used (Fura: 425 nm, Rhod123: 510 nm; Zeiss, Germany). Switching between wavelengths was achieved in less than 3 ms, allowing rapid ratiometric Ca\textsuperscript{2+} measurements. Calculations and analysis of intracellular Ca\textsuperscript{2+} concentrations and changes in \(\Delta\Psi\textsubscript{m}\) were performed offline after the experiment.

**Mitochondrial membrane potential measurements**

Rhod123 is used as an indicator of intactness of \(\Delta\Psi\textsubscript{m}\) (Mostafapour et al., 1997). \(\Delta\Psi\textsubscript{m}\) was monitored using rhod123. Adult (8-9 and 14-15 weeks) WT /SOD1\textsuperscript{G93A} mice brainstem slices were incubated in aCSF containing 0.5µg/ml rhod123 at room temperature for 15 min. Slices were washed with indicator-free medium at RT for >20 min before placed in the perfusion chamber for fluorescence analysis. Because of its positive charge rhod123 accumulates in mitochondria, where its fluorescence is quenched. Upon depolarization of \(\Delta\Psi\textsubscript{m}\), rhod123 is released from mitochondria and fluorescence increases. Rhod123 was excited at 485nm and a dichroic mirror with mid reflection at 510 was used to collect emission signal. Changes in rhod123 fluorescence are reported as relative values, \(F/F_0\), where \(F_0\) is the baseline fluorescence before stimulus or drug application.
**Microfluorometric Ca\(^{2+}\) measurements**

Measurements of intracellular calcium concentrations were performed as previously described (Lips and Keller, 1998). Changes in the intracellular Ca\(^{2+}\) concentration ([Ca\(^{2+}\)]\(_{i}\)) were monitored using fura-2 (K\(_d\) ~ 0.2 µM; Molecular Probes, Invitrogen, Eugene, OR, USA) after bath-loading the slices with the acetoxy methyl ester (AM) form of the dye (5µM, 40 min at 27°C). The slices were rinsed and incubated for further 30 min in aCSF for de-esterification of fura-2 AM prior to onset of imaging. Fura-2 was excited alternately at 360 and 390 by UV light using a computer-controlled monochromator and emitted light was directed to a dichroic mirror with mid-reflection at 425 nm and filtered by a band pass filter (505-530 nm; Zeiss). If not indicated otherwise, experiments were carried out at RT.

Fluorescence intensities of fura-2 were converted into Ca\(^{2+}\) concentrations according to Grynkiewicz et al. (Grynkiewicz et al., 1985), assuming K\(_d\) = 224 for HMNs (Lips and Keller, 1999; Ladewig and Keller, 2000). R\(_{\text{min}}\) and R\(_{\text{max}}\) were determined by exposing the cells to 15 µM ionomycin in the presence of aCSF either containing 0 mM Ca\(^{2+}\) and 10 mM EGTA or 10 mM Ca\(^{2+}\). Since in AM loaded slices the background fluorescence is not clearly determinable, we consider the calculated Ca\(^{2+}\) concentrations merely as an approximation of the real concentration. Therefore in figures, changes in [Ca\(^{2+}\)]\(_{i}\) are given as changes in fura-2 ratio (F/F\(_{0}\)) where F denotes the fluorescence values at different time points of experiment and F\(_{0}\) denotes the first fluorescence value. A change of 0.1 in fura-2 ratio corresponds to a change in [Ca\(^{2+}\)]\(_{i}\) of ~100 nM (For details see Bergmann and Keller, 2004). Further analysis was performed offline using IGOR Pro (Wavemetrics, Lake Oswego, OR, USA) and OriginLab (OriginLab Corporation, Northampton, MA, USA) Software.
Reagents

Fura-2 AM and rhod123 was purchased from Molecular Probes (Leiden, Netherlands). Carbonyl cyanide 4-trifluromethoxyphenylhydrazone (FCCP), cyclopiazonic acid (CPA) and oligomycin were purchased from Sigma-Aldrich Chemie (Deisenhoff, Germany). Stock solutions of chemicals were prepared as follows: FCCP (10mM) was dissolved in absolute ethanol (100%) and always keep the stock solution at 4°C (in an ice bath) during the whole experiment to avoid ethanol evaporation, CPA (10 mg/300µl) in DMSO and stored as 50µL aliquots at −20 °C. Fura-2 AM (50mg) dissolved in 50µL DMSO containing 10% pluronic acid. Rhod123 (10 mg/ml) was dissolved in ethanol (100%). Oligomycin was dissolved in DMSO (5 mg/ml). The corresponding drug was then included in the perfusate and bubbled with carbogen (95% O2, 5% CO2), at room temperature, before and during the experiments. We utilized 30mM KCl for depolarization.

Statistical analysis

Each brain stem slice was used for a single experiment, and includes more than one cell in fura-2 AM and rhod123 imaging experiments. Generally 2 slices used per mouse and 3-4 good cells taken from each slice for bar graph presentation. If not indicated otherwise, values in the text are given as mean ± standard error of the mean (SEM) and represent a minimum of 4±1 imaging experiments for 4±1 separate slices taken from indivisual mice. Error bars in figures represent SEM too. The significance after pharmacological intervention was calculated using Student’s t-test and one-way ANOVA. Further analysis was performed off-line using IGOR and Origin software, version 7.5.
Results

Pharmacological manipulation of motoneuron mitochondria by the mitochondrial uncoupler FCCP

To investigate the functional interplay between mitochondria and cytosolic calcium signaling, specific and rapidly acting pharmacological tools can be utilized. In this context, FCCP is widely used as a mitochondrial uncoupler that depolarizes the electrochemical potential by creating an ionic pore across the inner mitochondrial membrane (Billups et al., 2002; Duchen et al., 2003; Vergun et al., 2003). More specifically, FCCP is a lipophilic weak acid and, therefore, readily passes through surrounding cellular membranes. Besides disrupting ΔΨm, FCCP has been shown to abolish mitochondria-mediated calcium regulation and to cause the release of stored Ca^{2+} from mitochondria (Kanno et al., 2002; Feeney et al., 2003; Wyatt and Buckler, 2004; Jaiswal et al., 2006). The action of FCCP could be clearly studied based on its effect on the ΔΨm and ensuing [Ca^{2+}]i elevation, and it did not show any nonspecific effects on cell membrane potential. The probability of FCCP localization on the plasma membrane and any resulting Ca^{2+} leak was previously checked by monitoring the current across the cell membrane in voltage-clamped HMNs; this did not reveal any change (Bergmann and Keller, 2004).

First, we examined the changes in the ΔΨm of WT and SOD1^{G93A} mice. To measure this in brainstem slices, motoneurons were loaded with rhod123 and the corresponding changes in fluorescence were monitored in the HMNs using videomicroscopic fluoroscopy (Fig. 2). The measure of the spatial heterogeneity of the rhod123 signal is sensitive to the level of mitochondrial depolarization (Toescu and Verkhratsky, 2000). In juvenile animals, HMNs display a normalized fluorescence (F/F0) of 0.4546 ± 0.0391 and 0.4274 ± 0.0573 for WT and SOD1^{G93A} mice, respectively (Fig. 2, B and C). Essentially, there were no significant
differences. However, responses in adult WT animals were almost 3-fold higher compared to their SOD1\(^{G93A}\) littermates (0.3357 ± 0.0352 and 0.1106 ± 0.0406, respectively; \(p < 0.001\); Fig. 2, D and E). These observations indicate that mitochondria are significantly disturbed in symptomatic SOD1\(^{G93A}\) mice.

**Pharmacological manipulation of mitochondria in motoneurons by blocking \(F_1, F_0\)-ATP synthase**

It has been proposed that oligomycin inhibits \(F_1, F_0\)-ATPase activity by causing a conformational change in the \(F_0\) portion of the complex that is transmitted to \(F_1\) resulting in impaired substrate binding in the catalytic sites. Oligomycin inhibits ATP synthase by inhibiting the proton pump, thus preventing it from generating ATP. These observations of apparent conformational interactions between \(F_0\) and \(F_1\) on the mitochondrial membrane are relevant to the mechanism of the coupling device linking the energy store to ATP formation in oxidative phosphorylation (Stock et al., 1999).

To measure the impact of oligomycin on the \(\Delta\Psi_{mt}\), the brainstem slices were loaded with rhod123 and the corresponding changes in fluorescence monitored in juvenile and adult animals. Similar, but very weak, effects to those previously observed with the electron transport inhibitors (CN\(^-\)) were seen with oligomycin (Bergmann and Keller, 2004). As shown in Fig. 3, oligomycin’s impact on the normalized peak of rhod123 fluorescence in juvenile animals was 0.0475 ± 0.0156 and 0.0506 ± 0.0168 for WT and SOD1\(^{G93A}\) littermates, respectively (Fig. 3, A and B). Furthermore, in adult animals, normalized rhod123 fluorescence signals after oligomycin application were 0.0669 ± 0.0271 and 0.0526 ± 0.0270 for WT and SOD1\(^{G93A}\) littermates, respectively (\(p < 0.05\); Fig. 3, C-E).
Impact of plasma membrane depolarization on mitochondrial function in ALS vulnerable motoneurons

To determine the comparative efficiency of mitochondria upon depolarization and its influence on FCCP-evoked Δψm responses, HMNs from juvenile and adult brainstem slices were challenged with FCCP after K+ depolarization. Potassium stimulation evoked a prominent depolarization-induced mitochondrial signal. In juvenile animals, the normalized mean peak rhod123 fluorescence was 0.4123 ± 0.1104 and 0.3343 ± 0.0323 for WT and SOD1G93A littermates, respectively (p < 0.05; Data not shown; Quantitative fluorescence value compare in Table1). However, in adult WT animals, the response was almost 2.62-fold higher compared to SOD1G93A littermates (0.3288 ± 0.0928 and 0.1251 ± 0.0421, respectively; Student’s t-test, p < 0.001; Data not shown; Quantitative fluorescence value compare in Table1). Following previous trends, there was a very small difference in the responses of juvenile mice between two genotypes. However, exposure to FCCP after a depolarizing stimulus resulted in significant differences between the responses of adult WT and symptomatic SOD1G93A littermates at the late stage of motor dysfunction. These observations further indicate that mitochondria are significantly disturbed in symptomatic SOD1G93A mice.

Impact of plasma membrane depolarization and the inhibition of F1, F0-ATP synthase on FCCP-evoked responses of the Δψm

In addition to releasing various proapoptotic and toxic substances into the cytosol, mitochondrial membrane permeabilization has the potential to compromise oxidative phosphorylation. Impairment of the Δψm with FCCP may block oxidative phosphorylation and, in this state, glycolysis provides the primary means of ATP synthesis. The mitochondrial F1, F0-ATP synthase may reverse in a futile attempt to restore the Δψm when depolarized by...
FCCP, further depleting the ATP produced via glycolysis (Budd and Nicholls, 1996). Oligomycin was added with FCCP to prevent any accelerated consumption of cellular ATP by the reverse mode of ATP synthase operation (Budd and Nicholls, 1996; Babcock et al., 1997; David et al., 1998). After plasma membrane depolarization with K⁺, the mitochondrial membrane was permeabilized with FCCP and oligomycin. In juvenile animals, the HMNs displayed a normalized rhod123 fluorescence (F/F₀) of 0.7493 ± 0.0927 in WT (Fig. 4A) and 0.5501 ± 0.1903 in SOD1⁹³A (Fig. 4B, p < 0.05) mice, respectively. The impact of oligomycin on the peak amplitude of rhod123 fluorescence was nominal in juvenile mice and there was no significant difference between two genotypes (0.0256 ± 0.0096 and 0.0234 ± 0.0085, respectively). However, the response to FCCP plus oligomycin in adult WT (Fig. 4C; Table 1) mice was almost 2.29-fold higher compared to SOD1⁹³A littermates (0.3252 ± 0.0600 and 0.1416 ± 0.0316, respectively; p < 0.001; Fig. 4D; Table 1). The comparative details of normalized rhod123 signals in juvenile and adult animals are summarized in Fig. 4E.

Measurement of Ca²⁺-release responses in motoneurons
The aim of this study was to test the role of mitochondria as a Ca²⁺ buffer under physiological conditions. Accordingly, a fura-2 AM loading protocol was established that allows for the measurement of intracellular Ca²⁺ in motoneurons without disturbing intracellular structures, which generally occurs during patch-clamp recordings. This is advantageous because, besides protecting against “wash-out” and the rupturing of intracellular structures, the AM loading protocol allows for the specific stereotaxic and anatomical plane of the brainstem slices that protect it from mechanical aberration and substantially preserves a large fraction of the hypoglossal nerve and neuronal network. The procedure is outlined in Materials and
Methods. Changes in the Ca²⁺ concentration were reported as ratiometric (360/390 nm) normalized fluorescence (F/F₀).

**FCCP causes differential Ca²⁺ release and Ca²⁺ transients**

Blocking the mitochondrial Ca²⁺ uptake by application of FCCP for approximately 5 min has produced contrasting effects on the [Ca²⁺]ᵢ transient and decay time constant (τ) of ALS vulnerable or resistant motoneurons (Bergmann and Keller, 2004; Balakrishnan and Keller, unpublished data). It was also previously found that, in HMNs and facial motoneurons (FMNs), the presence of FCCP significantly delayed the τ (Balakrishnan and Keller, unpublished data). In the present study, there was no significant difference in the FCCP-evoked increase of [Ca²⁺]ᵢ between the brainstem slices of juvenile WT and SOD1<sup>G93A</sup> mice; the normalized peak fluorescence amplitude (F/F₀) after FCCP exposure was 0.1391 ± 0.0598 and 0.1244 ± 0.0535 for WT (Fig. 5B) and SOD1<sup>G93A</sup> (Fig. 5C) littermates, respectively. The kinetics of Ca²⁺ recovery in motoneurons was also similar in juvenile mice for both genotypes. However, in adult brainstem slices, the FCCP-evoked increase in [Ca²⁺]ᵢ was 0.1166 ± 0.0424 and 0.0533 ± 0.0316 for WT (Fig. 5D) and symptomatic SOD1<sup>G93A</sup> littermates (Fig. 5E), respectively. The average mean peak fluorescence intensity is summarized in Fig. 5F.

**Impact of plasma membrane depolarization on mitochondrial Ca²⁺ uptake and [Ca²⁺]ᵢ release**

The following pathways are responsible for the removal of Ca²⁺ from the cytosol: (i) accumulation in mitochondria, (ii) sequestration in the intracellular calcium-stores of the ER, and (iii) Ca²⁺ extrusion into the extracellular space by plasmalemmal Ca²⁺ pumps and/or Ca²⁺ exchangers (Pivovarova et al., 1999). Participation of all three pathways could be directly
confirmed in this study by utilizing different protocols. To analyze the comparative efficiency of mitochondria as a Ca\(^{2+}\) sequestering organelle, FCCP was applied to evacuate the mitochondria after the cells were exposed to a Ca\(^{2+}\) load evoked by a depolarizing stimulus, K\(^+\). When motoneurons were exposed to 30mM K\(^+\) for 20s, the [Ca\(^{2+}\)]\(_i\) increased rapidly and subsequently returned to the basal level, whereas mitochondria and ER retained large pools of Ca\(^{2+}\), presumably for later extrusion from the cell. To determine if the mitochondrial accumulation of Ca\(^{2+}\) has any apparent influence on the lifetime of the [Ca\(^{2+}\)]\(_i\) transient, and to test if a large Ca\(^{2+}\) pool exists, FCCP was added to the superfusate after K\(^+\) induced depolarization. In the case of juvenile brainstem slices, the application of FCCP within 5 minutes of depolarization induced by K\(^+\) resulted in a calcium release measured by the fura-2 fluorescence ratio (F/F0) of 0.1478 ± 0.0426 and 0.1312 ± 0.0468 for WT and SOD1\(^{G93A}\) littermates, respectively (Data not shown; Quantitative fluorescence value compare in Table 2). However, following previous trends there was a slight increase in the fluorescence after cell membrane depolarization compared to the fluorescence before depolarization (Fig. 5, B and C), but there was no significant difference in the FCCP-evoked responses (normalized, F/F0) between two genotypes. A similar application of FCCP in adult brainstem slices resulted in a Ca\(^{2+}\) release of 0.1416 ± 0.0458 and 0.0619 ± 0.0269 (F/F0) for WT and SOD1\(^{G93A}\) animals, respectively (Data not shown; Quantitative fluorescence value compare in Table 2). This implies that there is a significant difference between the motoneurons of WT and SOD1\(^{G93A}\) mice at the late stage of motor dysfunction in the Ca\(^{2+}\) accumulation activity of mitochondria.

*Pharmacological manipulation of ER in motoneurons by cyclopiazonic acid (CPA) inhibition of SERCA and its impact on differential Ca\(^{2+}\) store regulation*
The ER functions as an effective Ca\(^{2+}\) storing organelle. The active transport of [Ca\(^{2+}\)]\(_i\) into intracellular stores by sarco-endoplasmic reticulum Ca\(^{2+}\)-ATPase (SERCA) is important in regulating Ca\(^{2+}\) signaling (Cavagna et al., 2000). Moreover, inhibition of Ca\(^{2+}\) uptake by the ER has been shown to disrupt Ca\(^{2+}\) homeostasis (Trump and Berezesky, 1995). To test if the ER serves either of these roles in the motoneurons, we measured the calcium release from the ER in the presence of CPA, a specific inhibitor of the SERCA family of pumps (Simpson and Russel, 1997). The application of CPA evoked a rise in the [Ca\(^{2+}\)]\(_i\) transient (Fig. 6), which is indicative of Ca\(^{2+}\) leakage from the intracellular Ca\(^{2+}\) stores. The treatment caused a gradual release of Ca\(^{2+}\) from ER stores at basal condition and was recorded in both WT and SOD1\(^{G93A}\) mice brainstem slices for both juvenile and adult animals. The Ca\(^{2+}\) release (F/F0) in juvenile mice was 0.0857 ± 0.0382 and 0.0667 ± 0.0135 in WT and SOD1\(^{G93A}\) littermates, respectively (Fig. 6, A and B). In adult mice, the release of Ca\(^{2+}\) (F/F0) was 0.0817 ± 0.0332 and 0.0542 ± 0.0202 in WT and SOD1\(^{G93A}\) littermates, respectively (Fig. 6, C and D). In these experiments, the application of CPA resulted in more or less identical Ca\(^{2+}\) release responses, though in adult SOD1\(^{G93A}\) brainstem slices these values are slightly lower (p < 0.05; Student’s t-test and one-way ANOVA). The comparison of average HMN ER calcium release in juvenile and adult animals of different genotypes is presented in Fig. 6E.

Interaction between ER and mitochondria in differential Ca\(^{2+}\) store regulation and the role of the ER as a Ca\(^{2+}\) sequestering organelle

Evidence is building regarding the reciprocal functional interplay between the ER and mitochondria in response to various toxic agents in ALS, Alzheimer’s, and Parkinson’s disease (Paschen and Mengesdorf, 2005). It was previously shown in C. elegans that high intracellular Ca\(^{2+}\) levels and the release of ER-based Ca\(^{2+}\) stores are essential steps in the necrotic death mechanism of neurons (Xu K., 2001). Furthermore, Ca\(^{2+}\) release from the ER...
contributes to neuronal cell death because the Ca\(^{2+}\) release blocker, dantrolene, can protect neurons against bioenergetic failure and cellular damage (Wei and Perry, 1996). If this is true, the restoration of ER function or attenuation of the secondary dysfunction induced by ER could present a new, highly promising avenue for pharmacological intervention to minimize neuronal cell injury in the pathological states of ALS.

A comparative analysis of the Ca\(^{2+}\) storing ability of mitochondria and ER in juvenile and adult brainstem slices was done using FCCP and CPA. There was a significant quantitative difference between the ER and mitochondrial Ca\(^{2+}\) load in the case of healthy and ALS-vulnerable HMNs at the late stage of motor dysfunction; the Ca\(^{2+}\) release response was high in the mitochondria of WT mice. As shown in Fig. 7, in juvenile mice, the peak amplitude of mitochondrial Ca\(^{2+}\) release after application of FCCP plus CPA was 0.1738 ± 0.04659 and 0.1792 ± 0.0654 in WT and SOD1\(^{G93A}\) littermates, respectively (Fig. 7, A and B; Table 2). The impact of CPA on the peak amplitude of Ca\(^{2+}\) release was nominal compared to FCCP, indicating a lesser role for ER compared to mitochondria in Ca\(^{2+}\) storage, as exemplified by juvenile WT and SOD1\(^{G93A}\) mice (0.0342 ± 0.0087 and 0.0335 ± 0.0111, respectively; Fig. 7, A and B; Table 2). In adult mice, the peak amplitude of [Ca\(^{2+}\)]\(_i\) after CPA application was 0.0497 ± 0.0245 and 0.0311 ± 0.0087 for WT and SOD1\(^{G93A}\) littermates, respectively (p < 0.05), whereas the response to FCCP plus CPA was 0.2095 ± 0.0695 and 0.0967 ± 0.0284 for WT and SOD1\(^{G93A}\) littermates, respectively (p < 0.001; Fig. 7, C and D; Table 2). Comparative details of the normalized fura-2 ratio in juvenile and adult animals are summarized in Fig. 7E.
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Discussion

When rhod123-loaded HMNs were treated with FCCP, there was a sudden and reversible increase in fluorescence, indicating the transient loss of $\Delta \psi_m$. An increased response to FCCP in WT compared to SOD1$^{G93A}$ mice, which are at the symptomatic stage of motor dysfunction, supports the hypothesis that mitochondrial Ca$^{2+}$ homeostasis is significantly disturbed in SOD1$^{G93A}$ mice, and that mitochondria play a crucial role in motoneuron degeneration in the mouse model of hALS-fALS. Furthermore, we compared the efficiency of depolarization-induced mitochondrial responses after stimulation with K$^+$. Again, FCCP-evoked responses were significantly smaller in adult SOD1$^{G93A}$ compared to WT mice, suggesting impaired mitochondria.

We would expect that the ATP available for cellular processes, such as membrane Ca$^{2+}$ ATPases, would be lowest during bath application of FCCP. We found that bath application of oligomycin alone results in the inhibition of ATP via oxidative phosphorylation, and the $\Delta \psi_m$ remains intact due to cellular ATP being reduced but not depleted because of glycolysis. Under physiological conditions, mitochondrial uptake of calcium may occur via the calcium uniporter supported by the intact electrochemical gradient. However, oligomycin did not cause any significantly different postdepolarization and basal [Ca$^{2+}$]$_i$ regulation in either juvenile or adult WT and SOD1$^{G93A}$ littermates. These results indicate that, in contrast to FCCP, blockade of the mitochondrial F$_1$, F$_0$-ATP synthase by oligomycin is only associated with a minor impact on $\Delta \psi_m$ without discrimination of genotype or age. It was also noted that the reverse F$_1$, F$_0$-ATP synthase cycle or restoration of $\Delta \psi_m$ (Budd and Nicholls, 1996) was very rare and more likely to occur in adult SOD1$^{G93A}$ Tg mice. This could be due to several factors, including aging, vulnerable motoneurons, and the slow activity of the mitochondrial Na$^+$/Ca$^{2+}$ exchanger.
The impact of mitochondrial disruption on Ca\(^{2+}\) uptake and release.

Our interest in studying the role of Ca\(^{2+}\) regulation and the impact of mitochondrial inhibition on HMNs is based on several observations that mitochondria act as local calcium buffers, thus shaping the spatiotemporal aspects of [Ca\(^{2+}\)]\(_i\) signals. Mitochondria in HMNs and FMNs have a major percentage of cellular Ca\(^{2+}\) sequestered intracellularly after influx through the plasma membrane (Balakrishnan et al., 2004). In juvenile mice, we did not find any difference in the FCCP-evoked [Ca\(^{2+}\)]\(_i\) increase between two genotypes. However, the FCCP-evoked mitochondrial Ca\(^{2+}\) release responses (normalized) in WT adult mice were of a greater amplitude and substantially more prominent than those in corresponding SOD\(^1\)^G93A littermates. In the HMNs of adult SOD\(^1\)^G93A mice, mitochondrial Ca\(^{2+}\) release was much less after the preceding [Ca\(^{2+}\)]\(_i\) increase. This data indicates that the processes responsible for the release of [Ca\(^{2+}\)]\(_i\) are qualitatively different in adult WT and SOD\(^1\)^G93A mice. The main difference in the mitochondrial function of adult WT and SOD\(^1\)^G93A mice is their capability to accumulate a large amount of Ca\(^{2+}\) in rapidly in the motoneurons of WT mice compared to the delayed accumulation of much smaller amounts in SOD\(^1\)^G93A mice. The higher load of calcium in the HMNs of juvenile WT/SOD\(^1\)^G93A mice and adult WT mice can be attributed to the specialization of these cells to obtain Ca\(^{2+}\). This specialized property of HMN mitochondria could be vital in ALS pathology as the high glutamate concentration in synapses can lead to massive cellular entry and over-accumulation of [Ca\(^{2+}\)]\(_{\text{mito}}\), which is a conventional trigger for mitochondrial swelling and permeability transition. Under such circumstances, the HMNs of SOD\(^1\)^G93A mice in which the mitochondria buffer Ca\(^{2+}\) are at particular risk compared to other motoneurons, which are supplied with an abundance of Ca\(^{2+}\) chelating proteins. This supports the model that [Ca\(^{2+}\)]\(_{\text{mito}}\) homeostasis is significantly altered in SOD\(^1\)^G93A mice at the symptomatic stage of motor dysfunction.
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It has already been shown that the application of FCCP alone, without predepolarization, induces only small $[\text{Ca}^{2+}]_i$ elevations in motoneurons. However, if FCCP is applied immediately after the termination of depolarization during the decay of the induced transient, FCCP causes a large release of $\text{Ca}^{2+}$, demonstrating the effectiveness of the immediate uptake of $\text{Ca}^{2+}$ into the cell through plasmalemmal channels (Balakrishnan and Keller, unpublished data). In this study, FCCP was applied for a longer interval after the termination of depolarization. We observed that, when $\text{Ca}^{2+}$ returns to its basal level, it produces only a very small $[\text{Ca}^{2+}]_i$ increase, though the $\text{Ca}^{2+}$ store was approximately 2.28-fold greater in adult WT mice compared to SOD1$^{G93A}$ mice. The excess $\text{Ca}^{2+}$ that emerges in the second response seems to be hidden by the mitochondrial uptake of the first response. This data can be explained two ways: (i) the progressive leak of ions from the mitochondria back into the cytosol, and/or (ii) $\text{Ca}^{2+}$ homeostasis is significantly disturbed in vulnerable SOD1$^{G93A}$ motoneurons and mitochondria have a lower capacity to store $\text{Ca}^{2+}$ released by depolarization. Therefore, we conclude that the mitochondria in adult WT motoneurons are capable of retaining $\text{Ca}^{2+}$ for a longer time compared to vulnerable SOD1$^{G93A}$ motoneurons. The experiments also indicated that mitochondria contribute to the fast clearance of $\text{Ca}^{2+}$ transients by taking up approximately 50% of the motoneuron $\text{Ca}^{2+}$ loads, even for small $[\text{Ca}^{2+}]_i$ elevations (50-200 nM, physiological range; Balakrishnan and Keller observation). This is evident with the FCCP prevention of mitochondrial contributions to $\text{Ca}^{2+}$ uptake resulting in a severe delay in the $[\text{Ca}^{2+}]_i$ transient recovery time in symptomatic SOD1$^{G93A}$ mice.

Interaction of mitochondrial $\text{Ca}^{2+}$ stores with the endoplasmic reticulum

Different intracellular pools participate in the generation of $\text{Ca}^{2+}$ signals in neuronal cells, shaping their spatio-temporal patterns, and the cell life-death cycle (Herrington et al., 1996; Schinder et al., 1996). We found that the ER of HMNs retained a comparatively low amount
of calcium than mitochondria after \([\text{Ca}^{2+}]\), elevation, indicating its low efficiency at sequestering \(\text{Ca}^{2+}\) in the HMNs of adult WT and SOD1\(^{G93A}\) mice, which was slightly higher in juvenile mice. This indicates that the conventional mitochondrial \(\text{Ca}^{2+}\) storing function dominates \(\text{ER} \ \text{Ca}^{2+}\) accumulation in these motoneurons. Interestingly, CPA has a relatively weak effect on \(\text{Ca}^{2+}\) release in symptomatic SOD1\(^{G93A}\) mice, indicating that SOD1\(^{G93A}\) mutations might also result in defects in ER \(\text{Ca}^{2+}\) handling, which may perturb synaptic function while contributing to neurodegeneration. This data suggests that the ER of HMNs does not play a significant role in regulating \([\text{Ca}^{2+}]\), at the basal level or after imposed \(\text{Ca}^{2+}\) loads in juvenile WT or SOD1\(^{G93A}\) mice. However, in adult mice, during ALS progression, the ER does contribute some to the dysfunction of \(\text{Ca}^{2+}\) loads, suggesting that \(\text{Ca}^{2+}\) dysregulation due to the SOD1\(^{G93A}\) mutation is a late onset event and anticipates ALS progression.

The application of FCCP to CPA on HMNs clearly caused a separate \(\text{Ca}^{2+}\) release response. In adult WT HMNs, the ER \(\text{Ca}^{2+}\) release was slightly more than in SOD1\(^{G93A}\) mice, indicating that, in the context of the SOD1\(^{G93A}\) mutation, the ER may contribute at the late stage of motor dysfunction. Furthermore, the application of FCCP after emptying ER stores with CPA resulted in a separate release event, evident from the \([\text{Ca}^{2+}]\) increase. This release was higher than the general \(\text{Ca}^{2+}\) release caused by FCCP without emptying ER in juvenile WT and SOD1\(^{G93A}\) mice, but not in adult SOD1\(^{G93A}\) mice, which suggests an uptake of the released \(\text{Ca}^{2+}\) from ER by mitochondria in juvenile mice. This further indicates the explicit action of FCCP in our working model system and the existence of two separate intracellular \(\text{Ca}^{2+}\) stores, in which the ER appears to play a minimal role in buffering \([\text{Ca}^{2+}]\) after \(\text{Ca}^{2+}\) loads are imposed on the HMNs of SOD1\(^{G93A}\) mice, and the ER is most likely not impaired during ALS-related motoneuron disease. Our hypothesis is strengthened by the fact that we previously obtained similar results in a cell culture model of WT-SOD1 and SOD1\(^{G93A}\).
transfected SH-SY5Y cells. Caffeine selectively blocked Ca\textsuperscript{2+} uptake into the ER and mitochondrial compartments and affected its release from intracellular storage sites. The ryanodine receptor (RyR) led to a relatively slow and weak increase of [Ca\textsuperscript{2+}]i and [Ca\textsuperscript{2+}]mito, which occurred with slightly higher kinetics in WT cells than the SOD\textsuperscript{1G93A} transfected cells (Jaiswal et al., unpublished data). This explains that ER-dependent Ca\textsuperscript{2+} release is a minor contribution to mitochondria-mediated toxicity in SOD\textsuperscript{1G93A} HMNs as previously reported in other cell types and animal models (Murayama et al., 2000; Fill and Copello, 2002; Sher et al., 2007). This could indicate close coupling between these two organelles in healthy motoneurons. The results also indicate that, with ALS progression, close coupling between the ER and mitochondria is impaired.

Our results are in agreement with the “hotspot hypothesis” that mitochondria preferentially accumulate Ca\textsuperscript{2+} at microdomains of elevated [Ca\textsuperscript{2+}]i that exist near ER Ca\textsuperscript{2+} release sites and other Ca\textsuperscript{2+} channels. Accordingly, mitochondria may affect both Ca\textsuperscript{2+} release from the ER and capacitative Ca\textsuperscript{2+} entry across the plasma membrane, thereby shaping the size and duration of the [Ca\textsuperscript{2+}]i signal in the HMNs of WT and SOD\textsuperscript{1G93A} mice and the recruitment of these signals for selective motoneuron degeneration. The molecular mechanisms defining the organization of mitochondria in murine motoneurons in regards to the ER and other Ca\textsuperscript{2+} sources, and the extent to which mitochondrial function varies among different cell types, are questions that remain unanswered but are interesting areas for future investigations.

Potential impact for future neuroprotective strategies

The vulnerability of HMNs in ALS raises many questions, and the evident mitochondrial pathology observed in ALS patients and animal models suggest a central role for the degradation of mitochondrial integrity and metabolism by uncontrolled [Ca\textsuperscript{2+}]mito
accumulation leading to a vicious circle of pathological mechanisms finally transformed into a fatal cycle (Fig. 8). Given the mitochondrial disturbances, Ca\(^{2+}\) buffering becomes inefficient and cytosolic Ca\(^{2+}\) levels rise. The protective option is to increase the resistance of motoneurons to high intracellular Ca\(^{2+}\) concentrations by inducing defense mechanism and/or to inhibit the downstream pathways activated by increased [Ca\(^{2+}\)]\(_i\). However, severely impaired HMNs are prevented from taking advantage of neuronal protection, including a more defined separation of spatial Ca\(^{2+}\) gradient signal cascades. Moreover, recent research indicates that therapeutic options do not have to focus on motoneurons alone, as ALS seems to be a more intricate disease involving also glia, astrocytes, muscle, and in some cases inflammation and apoptosis. In conclusion, it seems that ALS is a multifactorial disease in which, under physiological conditions, diffusion-restricted and tightly controlled domains might indeed have several functional advantages. Accordingly, therapeutic measures aimed at protecting mitochondrial function could be useful in various forms of ALS. However, the surprisingly similar pathology of motoneuron degeneration in different forms of ALS provides an ongoing challenge to integrate the different aspects in a more unifying scheme. In this context, our results indicate that ΔΨ\(_m\), the inhibition of mitochondrial respiratory chain and energy production, and specialized Ca\(^{2+}\) homeostasis in motoneurons accounts for versatile and dynamic Ca\(^{2+}\) signaling, and are critical in ALS pathophysiology. They are also associated with a number of ALS-related risk factors, including low buffering, the important role of mitochondria in regulating [Ca\(^{2+}\)]\(_i\), and the presence of large and long-lasting Ca\(^{2+}\) domains. It is conceivable that a combination of therapies addressing the many intercellular targets in ALS could be successful at treating this once-obscure disease, though it is clear that more structural and functional studies are currently needed to identify potential cytosolic pathways and barriers leading to motoneuron degeneration in ALS. Forthcoming studies could add to the understanding of why these processes preferentially damage motoneurons.
and the function of non-cell autonomous cell death (glia and astrocytes), if any. Taken together, our observations support the notion that mitochondria significantly enhance the selective vulnerability of motoneurons in hALS and corresponding mouse models.

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References


Murayama T, Kurebayashi N and Ogawa Y (2000). Role of Mg$^{2+}$ in Ca$^{2+}$-induced Ca$^{2+}$ release through ryanodine receptors of frog skeletal muscle: modulations by adenine nucleotides and caffeine. *Biophys J* 78: 1810-1824.


Schinder AF, Olson EC, Spitzer NC and Montal M (1996). Mitochondrial dysfunction is a primary event in glutamate neurotoxicity. *J Neurosci* 16: 6125-33.


Footnotes

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Legends for Figures

Fig. 1. Preparation of brainstem slices from WT and SOD1<sup>G93A</sup> mice. (A) Position of the isolated mouse brainstem during slicing. The orientation of the brain stem is highlighted in the box. (B) CCD camera image of rhod123-stained acute mouse brainstem slice. The hypoglossal nucleus (paramedian below the fourth ventricle) is characterized by bright fluorescence, indicating that mitochondria have taken up a considerable amount of rhod123 before depolarization (modified from Bergmann et al., 2004). In the inset is a schematic drawing of the medulla oblongata from which slices were taken containing the hypoglossal nucleus (XII), ambiguous nucleus (NA), pre-Bötzinger complex (PBC), solitary tract nucleus (NTS), the spinal part of the trigeminal nucleus (SPV), and the inferior olive (IO; modified from Ramirez et al., 1997). (C) Illustration of the adult mouse brainstem slice containing hypoglossal motoneurons (HMNs) stained with different dyes. Left, a CCD camera image (4x4 binning) showing HMNs loaded with rhod123 (excitation at 485 nm). Right, a CCD camera image (4x4 binning) showing HMNs loaded with Fura-2 AM (excitation at 360 nm).

Fig. 2. Photomicrographs of rhod123-loaded brainstem slices from 8-9 week (juvenile) and 14-15 week (adult) mice and FCCP-induced mitochondrial depolarization of hypoglossal motoneurons (HMNs) in WT and SOD1<sup>G93A</sup> mouse brainstem slices. (A) Panels a and b display CCD camera images of rhod123-stained mouse brainstem slices from juvenile (pre-symptomatic) WT and SOD1<sup>G93A</sup> mice, respectively. Panels c and d display CCD camera images of rhod123-stained mouse brainstem slice from adult (symptomatic) WT and SOD1<sup>G93A</sup> mice, respectively. The black bar indicates FCCP perfusion, which quickly released the dye quenched by mitochondria. (B) The depolarization of HMNs juvenile WT and (C) SOD1<sup>G93A</sup> mice; (D) HMNs of adult WT and (E) SOD1<sup>G93A</sup> mice. The data represents a single cell from the brainstem slice imaged. Rhod123 fluorescence signals are represented.
as normalized (F/F0) values. (F) Bar diagram of FCCP-induced mitochondrial depolarization in the HMNs of juvenile and adult WT (N = 3; n = 15 and n = 19 cells, respectively) and SOD1<sup>G93A</sup> (N = 3; n = 13 and n = 17 cells, respectively) mice. The data represents at least three separate experiments perform in separate slice for each condition and is expressed as mean ± S.D.; N = number of experiments, n = number of cells, *p < 0.05 ***p < 0.001. The slice thickness in (A) is 200 μm. Scale bar 10 μm.

**Fig. 3.** Measurement of mitochondrial membrane potential (Δψ<sub>m</sub>) in brainstem slices incubated with oligomycin to inhibit F<sub>1</sub>, F<sub>0</sub>-ATP synthase and deplete Ca<sup>2+</sup> content. The application of 5 µg/ml oligomycin results in measurable changes in rhod123 fluorescence not only in the hypoglossal motoneurons (HMNs) of 8-9 week old juvenile WT (A) and SOD1<sup>G93A</sup> (B) mice, but also in 14-15 week old adult WT (C) and SOD1<sup>G93A</sup> (D) mice. The data represents a single cell from the slice imaged. The rhod123 fluorescence signals are represented as F/F0. (E) Comparison of the peak amplitude of rhod123 signals in WT (N = 2, n = 12 and N = 3, n = 18) and SOD1<sup>G93A</sup> (N = 2, n = 12 and N = 3, n = 18) mice at the pre-symptomatic (juvenile) and symptomatic (adult) stages of motor dysfunction, respectively. The data represents at least three separate experiments for each age and each genotype and is expressed as mean ± S.D.; N = number of experiments, n = number of cells, *p < 0.05.

**Fig. 4.** Impact of plasma membrane depolarization and inhibition of F<sub>1</sub>, F<sub>0</sub>-ATP synthase on FCCP-evoked responses of the mitochondrial membrane potential (Δψ<sub>m</sub>) in brainstem slices of juvenile (8-9 week) and adult (14-15 week) mice. Rhod123 fluorescence after stimulation-evoked Δψ<sub>m</sub> before and after application of oligomycin and FCCP in juvenile WT (A) and SOD1<sup>G93A</sup> (B) mice and adult WT (C) and SOD1<sup>G93A</sup> (D) mice. The horizontal black bars indicate the duration of K<sup>+</sup> induced plasma membrane
depolarization, stimulation with oligomycin, and stimulation with FCCP, respectively. (E) A graphical representation of the effect of oligomycin alone and oligomycin plus FCCP on the $\Delta \Psi_m$ in juvenile (N = 3) and adult (N = 3) WT (n =10 and n = 21, respectively) and SOD1$^{G93A}$ (n = 12 and n = 17, respectively) mice. Note that the $\Delta \Psi_m$ is not significantly affected by oligomycin in any of the mice, but that FCCP exhibits an increased rhod123 signal that significantly diminished in symptomatic (adult) SOD1$^{G93A}$ mice (**p < 0.001) compared to WT littermates (2.26 fold). Small differences in the rhod123 signals of juvenile mice (*p < 0.05) were also noted. The data is expressed as mean ± S.D.; N = number of experiments, n = number of cells. The data represents at least three separate experiments for each age and each genotype in separate slices.

Fig. 5. The impact of FCCP on differential cytosolic calcium ([Ca$^{2+}$]$_i$) release in juvenile (8-9 week) and adult (14-15 week) WT and SOD1$^{G93A}$ mice. (A) Photomicrographs of fura-2 AM loaded brainstem slices (200 $\mu$m thick) in juvenile (panels a and b) and adult (panels c and d) WT (panels a and c) and SOD1$^{G93A}$ (panels b and d) mice. The black bar indicates perfusion with FCCP, which quickly facilitates [Ca$^{2+}$]$_i$ release in the hypoglossal motoneurons (HMNs) of (B) juvenile WT and (C) SOD1$^{G93A}$ mice, and (D) adult WT and (E) SOD1$^{G93A}$ mice. The data represents a single cell from the slice imaged. (F) A bar diagram of FCCP-induced [Ca$^{2+}$]$_i$ release in the HMNs of juvenile and adult WT (N = 3; n = 14 and n =24, respectively) and SOD1$^{G93A}$ (N = 3; n = 14 and n = 21, respectively) mice. The fura-2 AM signal is represented as F/F0. The data represents at least three independent experiments for each genotype and is expressed as mean ± S.D.; N = number of experiments, n=Number of cells, ***p < 0.001. Scale bar 10 $\mu$m. The data represents at least three separate experiments for each age and each genotype in separate slices.
Fig. 6. Differential Ca\textsuperscript{2+} store regulation in the endoplasmic reticulum (ER) of juvenile and adult WT and SOD1\textsuperscript{G93A} mice. Brainstem slices were incubated with cyclopiazonic acid (CPA) to inhibit ER Ca\textsuperscript{2+}-ATPase and thereby deplete the Ca\textsuperscript{2+} content. The application of 50 μM CPA resulted in measurable Ca\textsuperscript{2+} release from the hypoglossal motoneurons (HMNs) of (A) juvenile WT and (B) SOD1\textsuperscript{G93A} mice, and (C) adult WT and (D) SOD1\textsuperscript{G93A} mice. The data represents a single cell from the slice imaged. Fura-2 AM signals are represented as F/F0. (E) Comparison of the amplitude of the ER calcium release in these motoneurons as a result of SERCA pump inhibition; the data represents at least three independent experiments (N = 3; n = 12) for each genotype. Data is expressed as mean ± S.D.; N = number of experiments, n = number of cells, *p < 0.05.

Fig. 7. Comparative analysis of the differential Ca\textsuperscript{2+} storage and regulation of the endoplasmic reticulum (ER) and mitochondria in juvenile and adult WT and SOD1\textsuperscript{G93A} mice. The hypoglossal motoneurons (HMNs) in brainstem slices were stimulated using FCCP and cyclopiazonic acid (CPA), which interfere with the integrity of the mitochondria and ER, respectively, and were used to release quenched calcium. Quantitative differences were evident in (A) juvenile WT and (B) SOD1\textsuperscript{G93A} mice, as well as (C) adult WT and (D) SOD1\textsuperscript{G93A} mice. The horizontal black bars indicate the duration of K\textsuperscript{+} induced depolarization, stimulation by CPA, and stimulation with FCCP plus CPA, respectively. The data represents a single cell from the slice imaged. Fura-2 AM signals are represented as F/F0. (E) A graphical representation of the comparison of Ca\textsuperscript{2+} release from the ER and mitochondria in HMNs from 8-9 week and 14-15 week old mice (N = 3) after application of CPA or CPA plus FCCP (n = 13). The data represents at least three independent experiments (n = 13) for each genotype and is expressed as mean ± S.D.; N = number of experiments, n = number of cells, ***p < 0.001, *p < 0.05.
Fig. 8. Pathological mechanisms in amyotrophic lateral sclerosis (ALS), a differential functional model of interactions between mitochondria and high Ca²⁺ levels. The compounds FCCP selectively depolarize hypoglossal motoneurons and increase their cytosolic Ca²⁺ ([Ca²⁺]ᵢ) load in vulnerable motoneurons. Events following the mitochondrial inhibition inhibit complex IV of the electron transport chain, which leads to reactive oxygen species (ROS) generation. The inhibition of the respiratory chain further decreases the mitochondrial membrane potential (ΔΨₘ) leading to reduced Ca²⁺ uptake into the mitochondrial matrix and the release of Ca²⁺ taken up during preceding activity. The risk becomes much higher when mitochondria are placed cardinaly to buffer the calcium and control the subsequent metabolic pathways as an uncontrolled elevation in [Ca²⁺]ᵢ can lead to immediate cell death. Mitochondrial inhibition additionally decreases cellular ATP levels, and this further enhances accumulation of [Ca²⁺]ᵢ. The observed changes provide a potential mechanism of how mitochondrial inhibition can lead to selective motoneuron degeneration.
Table 1. Impact of plasma membrane depolarization and inhibition of F$_1$, F$_0$-ATP synthase on FCCP-evoked responses. The rhod123 fluorescence (normalized peak amplitudes F/F0) measures mitochondrial membrane potential ($\Delta\Psi_m$) in brainstem slices from juvenile (8-9 week old) and adult (14-15 week old) WT and SOD1$^{G93A}$ mice.

<table>
<thead>
<tr>
<th>Rhod123 Fluorescence Unit (F/F0)</th>
<th>Juvenile mice</th>
<th>Adult mice</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WT</td>
<td>SOD1$^{G93A}$</td>
</tr>
<tr>
<td>Peak Amplitude</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCCP</td>
<td>0.4123 ± 0.1104</td>
<td>0.3343 ± 0.0323</td>
</tr>
<tr>
<td>FCCP+ Oligomycin</td>
<td>0.7493 ± 0.0927</td>
<td>0.5501 ± 0.1903</td>
</tr>
</tbody>
</table>

**p < 0.001 compared to WT. Data is expressed as mean ± S.D.
Table 2. Differential peak amplitudes of Ca\(^{2+}\) release from endoplasmic reticulum and mitochondria in brainstem slices from juvenile (8-9 week old) and adult (14-15 week old) WT and SOD1\(^{G93A}\) mice

<table>
<thead>
<tr>
<th>Fura-2 AM Ratio Unit (F/F0)</th>
<th>Ca(^{2+}) Peak Amplitude</th>
<th>Juvenile mice</th>
<th>Adult mice</th>
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<tr>
<td></td>
<td></td>
<td>WT</td>
<td>SOD1(^{G93A})</td>
</tr>
<tr>
<td>FCCP</td>
<td>0.1478 ± 0.0426</td>
<td>0.1312 ± 0.0468</td>
<td>0.1416 ± 0.0458</td>
</tr>
<tr>
<td>FCCP + CPA</td>
<td>0.1738 ± 0.0466</td>
<td>0.1792 ± 0.0654</td>
<td>0.2095 ± 0.0695</td>
</tr>
</tbody>
</table>

**p < 0.001 compared to WT. Data is expressed as mean ± S.D.
Figure 4
Figure 5
Figure 6
Figure 7
Figure 8

Normal Cellular Homeostasis in MN (WT) vs. Mitochondrial Degeneration in MN (SOD1<sup>G93A</sup>)

- **Na<sup>+</sup>**, **Ca<sup>2+</sup>**, **K<sup>+</sup>**
- HVA
- ATP
- Calcium binding protein
- Calcium

**FCCP, Oligo, CPA**

mtSOD1

Intermembrane space

- Complex I
- Complex II
- Complex III
- Complex IV

O<sub>2</sub>, H<sub>2</sub>O, ADP, ATP

Inner mitochondrial matrix