Dystrophic cardiomyopathy: amplification of cellular damage by Ca\textsuperscript{2+} signalling and reactive oxygen species-generating pathways

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Aims Cardiac myopathies are the second leading cause of death in patients with Duchenne and Becker muscular dystrophy, the two most common and severe forms of a disabling striated muscle disease. Although the genetic defect has been identified as mutations of the dystrophin gene, very little is known about the molecular and cellular events leading to progressive cardiac muscle damage. Dystrophin is a protein linking the cytoskeleton to a complex of transmembrane proteins that interact with the extracellular matrix. The fragility of the cell membrane resulting from the lack of dystrophin is thought to cause an excessive susceptibility to mechanical stress. Here, we examined cellular mechanisms linking the initial membrane damage to the dysfunction of dystrophic heart.

Methods and results Cardiac ventricular myocytes were enzymatically isolated from 5- to 9-month-old dystrophic \textit{mdx} and wild-type (WT) mice. Cells were exposed to mechanical stress, applied as osmotic shock. Stress-induced cytosolic and mitochondrial Ca\textsuperscript{2+} signals, production of reactive oxygen species (ROS), and mitochondrial membrane potential were monitored with confocal microscopy and fluorescent indicators. Pharmacological tools were used to scavenge ROS and to identify their possible sources. Osmotic shock triggered excessive cytosolic Ca\textsuperscript{2+} signals, often lasting for several minutes, in 82% of \textit{mdx} cells. In contrast, only 47% of the WT cardiomyocytes responded with transient and moderate intracellular Ca\textsuperscript{2+} signals. On average, the reaction was 6-fold larger in \textit{mdx} cells. Removal of extracellular Ca\textsuperscript{2+} abolished these responses, implicating Ca\textsuperscript{2+} influx as a trigger for abnormal Ca\textsuperscript{2+} signalling. Our further experiments revealed that osmotic stress in \textit{mdx} cells produced an increase in ROS production and mitochondrial Ca\textsuperscript{2+} overload. The latter was followed by collapse of the mitochondrial membrane potential, an early sign of cell death.

Conclusion Overall, our findings reveal that excessive intracellular Ca\textsuperscript{2+} signals and ROS generation link the initial sarcolemmal injury to mitochondrial dysfunctions. The latter possibly contribute to the loss of functional cardiac myocytes and heart failure in dystrophy. Understanding the sequence of events of dystrophic cell damage and the deleterious amplification systems involved, including several positive feed-back loops, may allow for a rational development of novel therapeutic strategies.

KEYWORDS
Calcium (cellular);
Mitochondria;
Myocytes;
Oxygen radicals;
SR (function)

1. Introduction

Dystrophinopathies result from mutations of the dystrophin gene (reviewed in Ervasti and Campbell\textsuperscript{1}). Dystrophin is a 427 kDa protein linking the cytoskeleton to a complex of transmembrane proteins, which interact with the extracellular matrix. Duchenne and Becker muscular dystrophy (DMD and BMD) are the two most common and severe forms and are characterized by progressive and disabling muscle weakness (one case per 3500 boys). Cardiac manifestations are present in essentially all patients by 20 years of age. The most common abnormality is dilated cardiomyopathy. Around 20% of the patients succumb from the cardiac manifestations. Clinically, the disease initially shows ECG abnormalities. Later, echocardiographic examinations reveal ventricular wall motion abnormalities in regions of fibrosis. With spreading of fibrosis, ventricular dysfunction and arrhythmias occur, ultimately leading to heart failure and sudden death.\textsuperscript{2} With improving medical care for the skeletal muscle weakness, the cardiac disease becomes more and more limiting for the survival of the patients.

In the skeletal muscle field, there is a significant body of data describing the cellular pathophysiological events (for review see Allen et al.\textsuperscript{3}). It is generally believed that
dystrophin deficiency leads to exaggerated sarcolemmal fragility. Abnormal Ca\textsuperscript{2+} influx and intracellular Ca\textsuperscript{2+} homeostasis after mechanical stress have been implicated in progressive death of dystrophic skeletal muscle fibres.\textsuperscript{4,5} The mdx mouse is a well-established model for skeletal muscle dystrophy, and it also develops a cardiac phenotype with age that is similar to the alterations observed in humans during dystrophic cardiomyopathy.\textsuperscript{6} It is suggested that in skeletal muscle, Ca\textsuperscript{2+} entry could occur via voltage-independent pathways,\textsuperscript{3} such as 'leak' channels,\textsuperscript{7} stretch-activated channels (SAC),\textsuperscript{8} or store operated channels (SOC).\textsuperscript{5} The molecular identity of these channels is not yet fully clear, but some of them are thought to contain TRP channel subunits.\textsuperscript{5} In addition, there are findings suggesting that the vulnerability of mdx muscle leads to microruptures which may also allow excessive Ca\textsuperscript{2+} influx.\textsuperscript{10} Despite all these identified possible pathways for Ca\textsuperscript{2+} entry, the main question still remains open: what is the sequence of cellular events that initiate Ca\textsuperscript{2+} influx and which are the positive feed-back loops that amplify this influx and lead to Ca\textsuperscript{2+} overload and cell death?

Identical questions apply to the cardiac phenotype, but much fewer studies were carried out to understand cellular mechanisms leading to cardiac pathology. However, the clinical findings described above and some experimental studies on the organ level also indicate an abnormal sensitivity of cardiomyocytes to mechanical stress, for example, after aortic banding\textsuperscript{11} or prolonged exposure to \beta-adrenergic stimulation to induce arterial hypertension.\textsuperscript{12} In addition, histological examination revealed replacement fibrosis and progressive deterioration of both tissues.

A functional study found a high stress sensitivity of isolated mdx cardiomyocytes and that the cell damage could be suppressed by the membrane protective detergent Poloxamer P188.\textsuperscript{15} In addition, a report suggested SAC to contribute to the abnormal Ca\textsuperscript{2+} influx pathway in mdx myocytes.\textsuperscript{16} Here, we used confocal imaging with various fluorescent indicators to monitor intracellular processes that may link the initial transmembrane Ca\textsuperscript{2+} influx to cell damage. We observed that mdx cardiac myocytes exhibit an extreme Ca\textsuperscript{2+} signalling response to mechanical stress. More importantly, we identified an abnormal activation of the Ca\textsuperscript{2+}-induced Ca\textsuperscript{2+} release signalling pathway together with an increased generation of reactive oxygen species (ROS) as two synergistic mechanisms contributing to the amplification of these Ca\textsuperscript{2+} signals. Preliminary results of these studies have been published as an abstract.\textsuperscript{17}
cells are also visualized in movies in the online supplement. **Figure 1B** shows the averaged changes in intracellular fluorescence in all studied WT and mdx cardiomyocytes, normalized to the resting values before osmotic shock. The stress-induced increase in fluorescence was larger and longer lasting in mdx cells compared with WT myocytes. The mean cellular fluorescence signal recorded during the first 60 s after returning to the iso-osmotic solution was 6-fold larger in mdx cells (**Figure 1C**).

### 3.2 A small Ca\textsuperscript{2+} influx is required for stress-induced Ca\textsuperscript{2+} signals in mdx cardiomyocytes

The above observation together with the recent results by Yasuda et al.\textsuperscript{15} suggest that mdx myocytes are more susceptible to membrane damage than WT cardiomyocytes. To test whether these Ca\textsuperscript{2+} signals depend on extracellular Ca\textsuperscript{2+}, we briefly removed Ca\textsuperscript{2+} from the extracellular solution. **Figure 2** shows that switching to a solution containing 0 mM Ca\textsuperscript{2+} completely abolished the response to osmotic shock. This observation confirms that Ca\textsuperscript{2+} entry is required, although the precise pathway(s) leading to Ca\textsuperscript{2+} influx into dystrophic cells are yet to be established and seems to involve multiple molecular entities.\textsuperscript{3}

Nevertheless, the increase in plasmalemmal permeability to Ca\textsuperscript{2+} and the slightly elevated resting Ca\textsuperscript{2+} concentration in mdx myocytes (see **Figure 2E** and Williams and Allen\textsuperscript{19}) alone are unlikely to explain the sustained Ca\textsuperscript{2+} signals in mdx cells subjected to osmotic shock. In cells treated with ryanodine (5 μM) and thapsigargin (500 nM) to eliminate the function of the sarcoplasmic reticulum (SR), a substantial Ca\textsuperscript{2+} influx during the superfusion with hypotonic solution would be visible as an increase of the cytosolic Ca\textsuperscript{2+} concentration. However, when applying a ratiometric indicator technique involving fluo-3 and fura-red to compensate for dye dilution due to osmotic swelling, only a modest elevation of the Ca\textsuperscript{2+} concentration was observed, suggesting that the Ca\textsuperscript{2+} influx was small (**Figure 2C** and D, gray circles).

### 3.3 Osmotic shock stimulates reactive oxygen species production

Because we were not able to detect a substantial Ca\textsuperscript{2+} influx during the shock, we suspected some intracellular mechanisms by which even small increases in [Ca\textsuperscript{2+}]\textsubscript{i} due to Ca\textsuperscript{2+} influx were amplified. One possibility could be oxidation of the cytosolic environment due to excessive ROS production,\textsuperscript{26} which could affect several proteins involved in intracellular Ca\textsuperscript{2+} homeostasis, most notably the ryanodine receptors (RyRs), thereby enhancing the sensitivity of SR Ca\textsuperscript{2+} release.

To test whether osmotic shock enhances ROS generation, we loaded myocytes with CM-H\textsubscript{2}DCFDA. In cells, this non-fluorescent compound is hydrolysed to DCFH and ROS generation is detected as a result of DCFH oxidation to DCF. **Figure 3A** shows images from one mdx cardiac myocyte before (image at 20 s), during (50 s), and after osmotic shock (80, 110, 140, and 170 s). Insets illustrate the banded fluorescence typical of a mitochondrial distribution. **Figure 3B** represents averaged and normalized fluorescence in mdx and wild-type (WT) mouse ventricular myocytes. **(A)** Images of Ca\textsuperscript{2+}-related fluorescence (fluo-3) obtained in mdx (left) and WT (right) myocytes subjected to osmotic shock. Ca\textsuperscript{2+} sparks and Ca\textsuperscript{2+} waves appear after the shock, much more pronounced in the mdx myocyte (left panel). **(B)** Time course of normalized fluorescence pooled from this protocol in mdx (black circles) and WT myocytes (white circles). Line on the top represents the protocol by which extracellular solutions were changed. **(C)** Mean values of normalized fluorescence averaged for each cell during 60 s after the osmotic shock (for B and C: n = 23 cells from N = 4 mice for mdx and n = 19, N = 3 for WT).
changes in DCF fluorescence in mdx and WT cells. To quantify the stress-induced changes in ROS production, we performed a linear fit to the fluorescence signal in each cell before and after osmotic shock. The slope of the DCF signal reflects the rate of ROS production. Before the osmotic shock, the ROS-related signals rose monotonically, presumably due to a basal generation of ROS. The initial slope was significantly larger in mdx myocytes than in WT cells (0.70 ± 0.09, n = 12 and 0.40 ± 0.07, n = 9, respectively) indicating an oxidative stress in these cells, as also suggested in Williams and Allen.27 Furthermore, we observed that the slope increased after the shock in both WT and mdx cells, but more in mdx myocytes than in WT cells [ratio of slopes before to after the shock was 1.72 ± 0.2 (n = 12) and 1.34 ± 0.12 (n = 9) in mdx and WT, respectively].

To confirm the involvement of ROS-dependent mechanisms in the generation of stress-induced Ca$^{2+}$ signals, we incubated mdx myocytes with 10 μM Mn-cpx3, a superoxide dismutase mimetic. Figure 4A shows that this ROS scavenger nearly eliminated cytosolic Ca$^{2+}$ transients produced by osmotic shock. After washing out the scavenger for 30 min, five out of six mdx cardiomyocytes recovered their exacerbated response. Figure 4B shows a significant decrease in the mean intracellular fluorescence recorded during the first 60 s after returning to an iso-osmotic solution in the presence of the scavenger.

There are several possible sources of ROS in cardiac myocytes that may be activated in response to mechanical stress. NAD(P)H oxidase (NOX) is known to be overexpressed in dystrophic heart27 and was found to be rapidly activated by osmotic swelling in astrocytes.28 Therefore, we tested whether NOX could be a source for a rapid increase in the ROS production in response to the mechanical stress in mdx myocytes. Cells were incubated for 30 min with the NOX inhibitor apocynin (0.2–1 mM). Figure 4C and D shows that the drug nearly eliminated the intracellular Ca$^{2+}$ signals induced by osmotic shock, suggesting NOX as a possible source of acute ROS production.

3.4 Excessive cytosolic Ca$^{2+}$ is taken up by the mitochondria

Mitochondria are well-established sources of ROS in myocardium subjected to acute or chronic mechanical stress.29

![Figure 2](image-url) Removal of extracellular Ca$^{2+}$ prevents stress-induced Ca$^{2+}$ signals while Ca$^{2+}$ influx during osmotic shock is small. (A) Time course of averaged normalized fluorescence in mdx cells during the osmotic shock under control conditions (black circles) and when Ca$^{2+}$ was briefly removed from the external solution (white circles). Bars at the bottom illustrate protocol by which extracellular solutions were changed. (B) Mean averaged fluorescence after the osmotic shock in the presence and absence of extracellular Ca$^{2+}$ (for 4 and 8: n = 5 cells from N = 2 mice for control and n = 6, N = 2 for zero Ca$^{2+}$). (C) Time course of averaged fluo-3/fura red ratio in mdx myocytes in control (black circles) and in the presence of ryanodine (ry, 5 μM) and thapsigargin (tg, 0.5 μM) (gray circles). (D) Mean [Ca$^{2+}$] before, during, and 60 s after the osmotic shock in control (n = 7, N = 3) and in the presence of ryanodine and thapsigargin (n = 8, N = 3). (E) Mean resting [Ca$^{2+}$] in wild-type and mdx cardiomyocytes (n = 70 and 59, N = 4 and 4 mice).

![Figure 3](image-url) Mdx cells generate more ROS than wild type and react more pronounced to osmotic shock. (A) Images of ROS related fluorescence (CM-H2-DCFDA) in mdx myocytes exposed to osmotic shock (insets show magnified region of interest indicated in first panel). (B) Averaged changes in normalized ROS signal in mdx (black circles) and wild-type (WT) (white circles) cells. Lines represent linear fits to the data. (C) Mdx myocytes generate more background ROS and after the stress their production of ROS increases more than in WT cells (n = 12 and 9, N = 3 and 3 mice). See Supplementary Material online for colour version.
Mitochondrial ROS could be responsible for the sustained cellular Ca\textsuperscript{2+} signals observed in mdx myocytes (note the gradual increase in ROS-related fluorescence in the mitochondrial regions later during the experiment shown in Figure 3). It is known that muscle cells continuously generate ROS, as a by-product of the mitochondrial respiratory chain, and that enhanced mitochondrial Ca\textsuperscript{2+} uptake stimulates further mitochondrial ROS production. We tested whether and to what extent mitochondria take up cytosolic Ca\textsuperscript{2+} after osmotic shock.

Mdtx and WT myocytes were loaded with the Ca\textsuperscript{2+} indicator rhod-2 and imaged with the identical experimental protocol. Rhod-2 is a charged molecule that preferentially partitions into the mitochondria. Figure 5A shows the mitochondrial rhod-2 distribution and the fluorescence signal in mdx myocytes before (image at 1 s), during (image at 28 s), and after the shock. Following 40 s of osmotic shock, fluorescence gradually increased within all mitochondria. Figure 5B shows the time course of rhod-2 signals in three groups of mitochondria indicated by regions of interest (1–3 in A). (C and D) Time course and averages showing suppression of the Ca\textsuperscript{2+} responses by the NOX inhibitor apocynin (data from n = 16 and 27 cells, N = 4 and 4 mice).

3.5 Osmotic shock induces mitochondrial depolarization in mdx cardiac myocytes

It is established that mitochondrial Ca\textsuperscript{2+} overload and the subsequent oxidative stress can lead to collapse of the mitochondrial membrane potential (ΔΨ\textsubscript{m}) and/or to the opening of the mitochondrial permeability transition pore (mPTP), ultimately causing necrotic/apoptotic cell death. Our results indicate that mitochondrial Ca\textsuperscript{2+} uptake is enhanced in mdx cardiac myocytes. We also found that some mitochondria lose Ca\textsuperscript{2+} after a period of initial accumulation, possibly as a result of irreversible mitochondrial depolarization. Therefore, we carried out experiments to directly monitor changes in mitochondrial membrane potential. TMRE is a charged dye, which distributes across the mitochondrial membrane in a voltage-dependent manner. Whenever the potential across the mitochondrial membrane dissipates, TMRE fluorescence is lost. Figure 6A shows one mdx cardiomyocyte loaded with 100 nM TMRE. A single mitochondrion (or a small group of mitochondria) can be visualized in each of the marked boxes. Subsequent to the osmotic shock, some mitochondria displayed irreversible loss of ΔΨ\textsubscript{m} whereas others did not. Changes in TMRE fluorescence for four individual mitochondria are plotted in Figure 6B. Note that the final level of TMRE signal is essentially the same in all four organelles, indicating their complete depolarization. Figure 6C compares the incidence and timing of osmotic shock-induced mitochondrial depolarization in mdx and WT cardiomyocytes. For each time point, we
calculated the number of polarized mitochondria in all cells of each type and normalized it to the total numbers of organelles imaged. In mdx cells, osmotic shock induced depolarization of ~2% of the mitochondria within 400 s of experimental recording (black line). Loss of TMRE signals by individual mitochondria was observed already 4 s after the shock. In contrast, in WT myocytes, the fraction of depolarized mitochondria was much smaller (0.3%) and the onset was later (100 s after the shock). It should be mentioned that in some mdx myocytes shock induced severe mitochondrial depolarization waves that resulted in complete collapse of $\Delta u_m$ across the entire cell within a few seconds. These cells were not included in the analysis presented in Figure 6C.

4. Discussion

Dystrophin-deficient cardiomyocytes are vulnerable to mechanical stress. Recently published work connects increased membrane fragility and stretch-induced $\text{Ca}^{2+}$ influx with death of dystrophic cells. In the present study, we identified two cellular signal amplification mechanisms that may link the fragility of the mdx cardiomyocyte membrane to later cell damage. As detailed below, the simultaneous activation of these two signal amplification systems is detrimental, because of bidirectional cross-talk with positive feed-back. Thus, the cellular response proceeds beyond the physiological limits, culminating in a chain of events, which may later end in apoptotic and/or necrotic cell death.

4.1 Amplification mechanisms

The massive $\text{Ca}^{2+}$ signals observed in mdx myocytes after osmotic shock were manifest as a surge of abundant spontaneous $\text{Ca}^{2+}$ sparks, regularly blending into $\text{Ca}^{2+}$ waves travelling along the cell. In resting cardiomyocytes such signals are the hallmark of abnormal $\text{Ca}^{2+}$-induced $\text{Ca}^{2+}$ release (CICR) activation and are commonly initiated by overloading the SR with $\text{Ca}^{2+}$ in the course of various noxious conditions. The importance of CICR for the observed signal amplification was also emphasized by the absence of such $\text{Ca}^{2+}$ signals in cells pretreated with ryanodine and thapsigargin. However, for $\text{Ca}^{2+}$ overload to develop in a short period of time (i.e. during the exposure to hypotonic solution), $\text{Ca}^{2+}$ influx has to be substantial. Surprisingly, such a massive $\text{Ca}^{2+}$ influx could not be detected in our experiments, even though the behaviour of the myocytes in zero $\text{Ca}^{2+}$ indicated an important role for at least some minor transsarcolemmal $\text{Ca}^{2+}$ influx. The obvious discrepancy between massive and rapid CICR activation despite minimal $\text{Ca}^{2+}$ entry and only slightly elevated resting $\text{Ca}^{2+}$ levels led us to consider additional mechanisms that could make the RyR rapidly more sensitive and provoke spontaneous $\text{Ca}^{2+}$ signals without pronounced SR $\text{Ca}^{2+}$ overload.

ROS have been implicated in changing gating and $\text{Ca}^{2+}$ sensitivity of the RyRs via redox modifications of the channels. Furthermore, increased ROS generation after mechanical stretch has been reported even in normal cardiac muscle. Our findings revealed an elevated basal rate of ROS production in mdx cells. Furthermore, mechanical stress led to enhanced ROS production in all cardiomyocytes, but significantly more pronounced in mdx cells. Although the first finding may underlie the propensity of mdx cells to overreact after small $\text{Ca}^{2+}$ influx signals, the latter may be a consequence of the larger $\text{Ca}^{2+}$ signals in these cells. As one might expect based on these findings, ROS scavengers reversibly suppressed the excessive stress-induced $\text{Ca}^{2+}$ signalling in mdx cells. Taken together, our results suggest that the change of the cytosolic oxidative environment due to increased [ROS] promotes the abnormal CICR activation without pronounced $\text{Ca}^{2+}$ overload.

ROS generation in response to mechanical forces may originate from several sources, including the NOX, xanthine oxidase, or other oxidase systems, such as nitric oxide oxidase, and mitochondria. Our results with the NOX inhibitor apocynin suggest an involvement of this source of ROS. Owing to its overexpression in dystrophic heart and due to its rapid activation by osmotic swelling, this source of ROS may be particularly important in the early phases of the response. It is also established that an elevation in mitochondrial $\text{Ca}^{2+}$ subsequent to prolonged cytosolic $\text{Ca}^{2+}$ signal activity stimulates mitochondrial ROS production. Consistent with this notion, we observed increased $\text{Ca}^{2+}$ levels in cardiac mitochondria following the osmotic shock that were significantly larger in mdx cells.
4.2 Cross-talk between Ca\textsuperscript{2+}-induced Ca\textsuperscript{2+} release and reactive oxygen species

CICR and ROS generation are two signalling pathways that exhibit a high degree of positive feed-back. Either mechanism could lead to the observed massive Ca\textsuperscript{2+} signals. However, the combination of both pathways being activated together may have even more severe consequences, as both pathways exhibit mutual and synergistic cross-talk with each other. For example, ROS could promote RyRs openings as pathways exhibit mutual and synergistic cross-talk with each other. Taken together, the simultaneous activation of these signalling pathways is particularly destructive for the cells because it has a tendency to escalate into mutually synergistic positive feed-back signalling loops.

4.3 Link between abnormal cellular signalling and pathology of the heart

Although WT myocytes survive the initial Ca\textsuperscript{2+} overload, the strong activation of several pathways may overwhelm the cellular defence mechanisms in mdx cells. It has been postulated for many years that proteases are a downstream Ca\textsuperscript{2+} activated target involved in protein degradation and necrosis of dystrophic skeletal muscle. Calpain is considered to be a likely candidate, as its expression is greater in mdx muscle. Because calpain is expressed in heart, and because calpain inhibitors protect from ischaemia-reperfusion injury, it is likely that this protease forms a part of the cellular death pathway in mdx heart.

Under pathological conditions, cytosolic and mitochondrial Ca\textsuperscript{2+} overload and/or excess in ROS can lead to opening of the mPTP, which is accompanied by a dissipation of the mitochondrial membrane potential and usually precedes necrotic/apoptotic cell death. Our data reveal multiple mitochondrial dysfunctions in mdx cardiac myocytes following osmotic stress. In particular, they show mitochondrial Ca\textsuperscript{2+} overload, increased ROS production, irreversible depolarization of the mitochondrial membrane, which can be a direct indication of mPTP opening. Apoptotic and necrotic cells have been observed in cardiac tissue of dystrophy patients and mdx mice. Lost cardiomyocytes cannot regenerate and are likely to be replaced by connective tissue, ultimately leading to the observed fibrosis.

At present, several studies are conducted to develop treatments of the cardiac dystrophic phenotype by either replacing the lost cardiomyocytes with stem cell approaches or to make the myocytes mechanically less vulnerable by gene transfer of dystrophin, utrophin, or functional dystrophin fragments (microdystrophins). Notably, mdx mice can partly compensate for the lack of dystrophin by adaptive upregulation and redistribution of the protein utrophin. An mdx mouse lacking utrophin presents with a more severe phenotype, particularly in skeletal muscle, but also in cardiac muscle. Although cell replacement therapies will obviously only be able to treat late stages of the disease, curative gene therapy may require a long time to develop for routine application. In the meantime, it would be helpful to implement pharmacological treatment options which are able to slow down the progression of the disease. Considering the early cellular stress responses reported here, this might be accomplished by interfering with any of the early cellular events leading to excessive Ca\textsuperscript{2+} and ROS signals.

Supplementary material

Supplementary material is available at Cardiovascular Research online.

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