Peroxisomes contribute to intracellular calcium dynamics in cardiomyocytes and non-excitable cells

Yelena Sargsyan1, Uta Bickmeyer1, Christine S Gibhardt2, Katrin Streckfuss-Bömeke3,4,6, Ivan Bogeski2, Sven Thoms1,5,6

Peroxisomes communicate with other cellular compartments by transfer of various metabolites. However, whether peroxisomes are sites for calcium handling and exchange has remained contentious. Here we generated sensors for assessment of peroxisomal calcium and applied them for single-cell-based calcium imaging in HeLa cells and cardiomyocytes. We found that peroxisomes in HeLa cells take up calcium upon depletion of intracellular calcium stores and upon calcium influx across the plasma membrane. Furthermore, we show that peroxisomes of neonatal rat cardiomyocytes and human induced pluripotent stem cell-derived cardiomyocytes can take up calcium. Our results indicate that peroxisomal and cytosolic calcium signals are tightly interconnected both in HeLa cells and in cardiomyocytes. Cardiac peroxisomes take up calcium on beat-to-beat basis. Hence, peroxisomes may play an important role in shaping cellular calcium dynamics of cardiomyocytes.

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Introduction

Calcium ions (Ca\(^{2+}\)) play a decisive role in the regulation of many cellular processes and inter-compartment communication, especially in excitable cells such as neurons or cardiomyocytes (CMs) (Clapham, 2007). In CMs, for example, cytosolic Ca\(^{2+}\) directly engages in cell contraction. At the same time, mitochondrial Ca\(^{2+}\) coordinates ATP production and energy demand in CMs (Williams et al., 2015), highlighting the importance of intracellular organelles in Ca\(^{2+}\) redistribution. The main sites of Ca\(^{2+}\) entry to the cell and intracellular calcium signal regulation are the plasma membrane (PM) and intracellular calcium stores, in particular those of the ER (Paupe & Prudent, 2018).

Excess of organellar Ca\(^{2+}\) can be detrimental for health. Elevated mitochondrial uptake increases mitochondrial reactive oxygen species (ROS) production and is associated with heart failure and ischemic brain injury (Starkov et al., 2004; Santulli et al., 2015). Reversely, mitochondrial ROS decrease if Ca\(^{2+}\) uptake to mitochondria is suppressed (Mallilankaraman et al., 2012; Tomar et al., 2016). Understanding principles and mechanisms of organellar Ca\(^{2+}\) handling provides a starting point to develop interventions in dysregulated calcium handling.

Peroxisomes are small intracellular organelles with a phospholipid bilayer membrane. In concert with evolutionarily conserved functions in lipid and redox metabolism, peroxisomes are highly plastic and change in their number, morphology and content upon environmental stimuli (Smith & Aitchison, 2013). Communication of peroxisomes with other cellular compartments through exchange of ROS or lipid metabolites is essential for human health (Wanders et al., 2015; Castro et al., 2018; Schrader et al., 2020). Yet, peroxisomal Ca\(^{2+}\) has not been studied in excitable cells before, and there are contradicting data about the Ca\(^{2+}\) handling in peroxisomes and its dependence on cytosolic Ca\(^{2+}\) (Drago et al., 2008; Lasorsa et al., 2008). It has been suggested that peroxisomes are potential targets of Ca\(^{2+}\) signalling pathways that initiate outside of the peroxisome or serve as a cytosolic Ca\(^{2+}\) buffer, but peroxisomes may also take up Ca\(^{2+}\) due to their own need (Drago et al., 2008; Islinger et al., 2012).

Measurement of Ca\(^{2+}\) dynamics in vivo inside cellular organelles was driven by the development of Ca\(^{2+}\)-sensitive fluorescent proteins, also known as genetically encoded Ca\(^{2+}\) indicators (GECIs) (Pozzan & Rudolf, 2009; Gibhardt et al., 2016). Ca\(^{2+}\) dynamics was analysed in the ER, in mitochondria, the cytosol, and in lysosomes by using GECIs (Whitaker, 2010; McCue et al., 2013). GECIs have a Ca\(^{2+}\)-binding domain, usually CaM. Ratiometric pericam is a single fluorophore-based GECI with circularly permutated EYFP (cpEYFP) as fluorophore (Nagai et al., 2001). GECIs play a special role among cameleon-based sensors that use Förster resonance energy transfer (FRET). Here, Ca\(^{2+}\) results in a conformational change that decreases the distance between donor (typically CFP) and acceptor (typically a YFP variant) enabling FRET (Palmer & Tsien, 2006; Pérez Koldenkova & Nagai, 2013; Gibhardt et al., 2016) (Fig 1A).

 Patients with adult Refsum disease due to peroxisome biogenesis disorder develop cardiac arrhythmias and heart failure at advanced disease stages (Wanders & Komen, 2007). As the heart muscle uses fatty acids as its main energy source, peroxisome...
localised lipid metabolism is thought to be especially important for the heart (Colasante et al., 2015). The cardioprotective effects of peroxisomes are also attributed to their role in redox homeostasis (Colasante et al., 2015). However, if peroxisomes directly participate in cellular Ca\(^{2+}\) homeostasis, they may have also antiarrhythmic effects independent of their metabolic roles.

This work combines the advantages of organelle-targeted GECIs and human induced pluripotent stem cells (hiPSCs). We develop new sensors for peroxisomal Ca\(^{2+}\). (A) Genetically encoded calcium indicators (GECIs) targeted to peroxisomes. D3cpV-px and D1cpv-px are Förster resonance energy transfer (FRET) sensors with modified CaM sites. Pericam-px is a single fluorophore-based GECI that has M13 and CaM as Ca\(^{2+}\)-binding sites. In the absence of Ca\(^{2+}\), the emission measured when the sensor is excited with 420 nm is higher than when excited with 505 nm. The ratio 505/420 is a measure for the Ca\(^{2+}\) concentration. (B) Subcellular localisation of GECIs used in this study. (C) Peroxosomal GECIs colocalise with the peroxisomal membrane marker PEX14 or PMP70. HeLa cells were transfected with the GECIs and stained with anti-PEX14 or anti-PMP70 antibodies. The images in the left part of the panel show one cell each (scale bar 10 μm). The cropped areas are marked and magnified in the right part of the panel (scale bar 2 μm). (D, E, F) D3cpV-px, D1cpv-px, and pericam-px are Ca\(^{2+}\) sensitive. Images false-colored with look-up table show representative cells before (left) and after (right) Ca\(^{2+}\) addition. Curves presented as mean ± SEM. Scale bar: 10 μm. (D) Addition of 1 mM Ca\(^{2+}\) to D3cpV-px expressing cells results in 1.5-fold FRET ratio increase, n = 60 cells from three independent experiments. (E) FRET ratio increases 1.08 times when 1 mM Ca\(^{2+}\) is added to D1cpv-px expressing cells, n = 33 cells from three experiments. (F) Ca\(^{2+}\) addition leads to 1.5-fold increase in 505/420 ratio with pericam-px, n = 75 cells from three experiments. (G) Measurement of D3cpV-px during cytosol washout. No change in signal is detected. (H) Measurement of pericam-px during cytosol washout. No difference of signal before and after cytosol washout is detected, n = 43 cells for D3cpV-px in (G) and n = 45 cells for pericam-px in (H).
several peroxisomal Ca\textsuperscript{2+} sensors, and we measure intraperoxisomal Ca\textsuperscript{2+} after pharmacological stimulation in non-excitable and excitable cells. We show that peroxisomes take up Ca\textsuperscript{2+} upon cytosolic Ca\textsuperscript{2+} increase after both ER Ca\textsuperscript{2+}-store depletion and Ca\textsuperscript{2+} entry to the cells through PM. We also demonstrate that peroxisomes take up Ca\textsuperscript{2+} in rat CMs and hiPSC-CMs.

Results

Development and validation of Ca\textsuperscript{2+} sensors for peroxisomal Ca\textsuperscript{2+}

To assess peroxisomal Ca\textsuperscript{2+}, we used three GECIs with different affinities to Ca\textsuperscript{2+}: D3cpV, D1cpV, and ratiometric pericam (Fig 1A and Table 1). The sensors were chosen to cover a wide range of K\textsubscript{d} values to identify the most suitable GECI for intraperoxisomal measurement. We preferred ratiometric sensors that allow measurements in two wavelengths. This enables direct interpretation of the acquired data by calculating the ratio of intensities at each time point. The ratios provide direct information about Ca\textsuperscript{2+} concentration and are independent of the sensor expression itself (Perez Koldenkova & Nagai, 2013). For the straight comparison of cellular compartments, we used specific sensors for the cytosol (D3cpV and R-GECO1), mitochondria (amtd3cpV and R-GECO-mito), and peroxisomes (D3cpV-px, D1cpV-px, and pericam-px) (Fig 1B).

D3cpV is a cameleon-type indicator based on FRET. The conformational change associated with the Ca\textsuperscript{2+} binding to CaM leads to an increase in FRET efficiency and FRET ratio (Perez Koldenkova & Nagai, 2013). D3cpV has an in vitro K\textsubscript{d} value of 0.6 μM and a dynamic range of 5.0 (Palmer et al, 2006). D1cpV, in comparison, is a FRET sensor with a K\textsubscript{d} value of 60 μM (Palmer et al, 2004). Finally, pericam is a cpEYFP-based GECI with two excitation peaks at ~420 and ~505 nm (Nagai et al, 2001). In the presence of Ca\textsuperscript{2+}, a conformational change associated with the Ca\textsuperscript{2+} binding to CaM leads to a change in the pericam structure shifts the excitation profile so that the 505/420 ratio increases and serves as a measure of Ca\textsuperscript{2+} concentration (Fig 1A). Pericam has a K\textsubscript{d} value of 1.7 μM and dynamic range of 10.

We added strong peroxisomal targeting signals of the PTS1 type to D3cpV, D1cpV, and pericam and tested their localisation after transfection by co-staining with antibodies directed against the peroxisomal membrane protein PEX14. All constructs targeted to the peroxisome (Fig 1C).

To test if D3cpV-px senses Ca\textsuperscript{2+} in peroxisomes of living cells, we permeabilized cells by digitonin, washed out the cytosol, and added 1 mM Ca\textsuperscript{2+}. Ca\textsuperscript{2+} addition resulted in drastic increase of FRET and a 1.5-fold increase in FRET ratio (Fig 1D). To illustrate the increase of the FRET signal, we false-colored the images recorded before and after Ca\textsuperscript{2+} addition by using a color look-up table (LUT) (Fig 1D).

When we performed the same type of experiment with D1cpV-px, FRET increased as well after Ca\textsuperscript{2+} addition, showing that the D1cpV-px construct is Ca\textsuperscript{2+} sensitive (Fig 1E). However, following the same stimulation protocol, the signal change of D1cpV-px was only 1.08-fold, and thus considerably smaller than for D3cpV-px. Because of the low signal change, we excluded D1cpV-px from further experiments on peroxisomal Ca\textsuperscript{2+}. Using pericam-px, the third peroxisome-targeted sensor in this set of experiments, high concentration of Ca\textsuperscript{2+} addition after digitonin treatment resulted in 1.5-fold increase similar as for D3cpv-px (Fig 1F). Based on these results we decided to use D3cpV-px and pericam-px to evaluate Ca\textsuperscript{2+} dynamics in peroxisomes.

To study possible mislocalisation or residual signal of peroxisomal Ca\textsuperscript{2+} sensors from the cytosol, we analysed the peroxisomal Ca\textsuperscript{2+} signals after digitonin permeabilisation of intact cells. If the sensor was partially mislocalised to the cytosol, we would expect a signal decrease after permeabilisation with digitonin. We first tested this in D3cpV-px (Fig 1G). There was no signal change observed, suggesting that D3cpv-px has no cytosolic mislocalisation. The cytosol washout also did not change the Ca\textsuperscript{2+} signal of the pericam-px before and after digitonin treatment, suggesting that pericam-px, like D3cpv-px, is exclusively localised to the peroxisome (Fig 1H). The quantification of D3cpv-px colocalisation with peroxisomal enzyme catalase in comparison with peroxisomal membrane protein PMP70 and catalase colocalisation revealed no differences, suggesting residue-free targeting of the GECI to peroxisomes (Fig 2A).

Peroxisomal Ca\textsuperscript{2+} in non-excitable cells largely follows cytosolic Ca\textsuperscript{2+}

We first aimed to exclude that potential differences of cytosolic and peroxisomal pH lead to differences in the performance of our GECIs in these cell compartments. Therefore, we exposed the cells transfected with either D3cpV or with D3cpV-px to different pH buffers containing the proton ionophore nigericin (Fig 2B). In the range of physiological cytosolic pH (7.2, Casey et al, 2010) and peroxisomal pH (between 7.0 and 8.0, depending on the cell type and source, Godinho & Schrader, 2017), the sensors showed stable FRET ratios. As a control, we also exposed the sensors to pH 4.0, Table 1. Key properties of the genetically encoded Ca\textsuperscript{2+} indicators (GECIs) for cytosol and peroxisome.

<table>
<thead>
<tr>
<th>Cytosolic GECIs</th>
<th>Peroxisomal GECIs (this study)</th>
</tr>
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<tbody>
<tr>
<td><strong>Construct Name</strong></td>
<td><strong>K\textsubscript{d} (in vitro)</strong></td>
</tr>
<tr>
<td>D3cpV</td>
<td>0.6 μM\textsuperscript{a}</td>
</tr>
<tr>
<td>D1cpV</td>
<td>60 μM\textsuperscript{b}</td>
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<tr>
<td>Ratiometric-pericam</td>
<td>1.7 μM\textsuperscript{d}</td>
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</tbody>
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\textsuperscript{a}References: Palmer et al (2006).
\textsuperscript{b}Palmer et al (2004).
\textsuperscript{c}Greotti et al (2016).
\textsuperscript{d}Nagai et al (2001).
Figure 2. Measurement of peroxisomal Ca\textsuperscript{2+} in HeLa cells.

(A) Quantification of D3cpV-px colocalisation with peroxisomes. Mander’s colocalisation coefficient was normalised to PM70 and catalase colocalisation, which was set to 1. n = 5.

(B) Förster resonance energy transfer ratio measured at different pH values for D3cpV (cyto) and D3cpV-px (pero). Cells were incubated in buffers with different pH values containing 10 μM nigericin. Cyto and pero show comparable results at physiological pH values of cytosol and peroxisomes. At the pH = 4 the Förster resonance energy transfer ratio decreases drastically because of the acceptor sensitivity. Cell numbers for cyto at pH 4 n = 51, 7.1 = 51, 7.35 = 51, 7.5 = 67, 7.65 = 64, 7.8 = 64 from three independent experiments per condition.

(C) Comparison of cytosolic and peroxisomal responses to ionomycin (Iono). In comparison to cytosol, peroxisomal signal increases gradually, n = 16 cells for D3cpV and n = 9 cells for D3cpV-px.

(D) One-step experiment in HeLa cells with thapsigargin (Tg) addition in Ca\textsuperscript{2+}-containing buffer. Cytosolic and peroxisomal Ca\textsuperscript{2+} increase upon Tg treatment. n = 31 (cyto), 30 (pero) from four (cyto) and five (pero) independent experiments.
which resulted in drastic decrease in FRET ratio due to the pH sensitivity of the acceptor (Fig 2B).

We then aimed to compare the maximal possible response of cytosol and peroxisomes to Ca\textsuperscript{2+}. For this purpose, we used ionomycin as an ionophore. Ionomycin resulted in fast and immediate increase in the cytosolic signal (Fig 2C). The peroxisomal signal also increased, yet more slowly. After reaching its maximum, it decreased gradually and in 12 min nearly returned to its starting values. The cytosolic signal decreased to its half maximal response in the same time with the most significant decrease observed in the first 2 min after the maximum (Fig 2C). These observations suggest that there could be differences between peroxisome and cytosol in Ca\textsuperscript{2+} handling also under near-physiological stimulation.

Furthermore, we compared the response of cytosol and peroxisomes to milder cytosolic Ca\textsuperscript{2+} increase stimulated with thapsigargin (Tg) as a sarcoplasmic/endoplasmic reticulum calcium ATPase (SERCA) inhibitor (Fig 2D). SERCA pumps Ca\textsuperscript{2+} constantly back to the ER store (Clapham, 2007), upon its inhibition Ca\textsuperscript{2+} accumulates in the cytosol. When cytosolic Ca\textsuperscript{2+} increased gradually, we observed a difference only in maximal signals between peroxisome and cytosol.

Based on the Ca\textsuperscript{2+} measurements in other organelles (Zhao et al, 2011; Matsuda et al, 2013; Suzuki et al, 2014; Petzungaro et al, 2015), we developed an experimental paradigm for peroxisome responses to the depletion and refilling of intracellular Ca\textsuperscript{2+} stores, specifically ER, in non-excitable HeLa cells at near-physiological situation (Fig 2E). The stimulation of cell-surface localised G-protein-coupled receptors by 100 µM histamine results in the activation of phospholipase C cascade. Inositol 1,4,5-trisphosphate (IP\textsubscript{3}), the product of the cascade, binds to the IP\textsubscript{3} receptor on the ER membrane, triggering Ca\textsuperscript{2+} store release. The cells are then exposed to 1 mM extracellular Ca\textsuperscript{2+}, which leads to store-operated Ca\textsuperscript{2+} entry and a second Ca\textsuperscript{2+} elevation in the cytosol.

To confirm that this stimulation protocol does not result in changes of the acceptor fluorophore (YFP or Venus) signal of the GECI (e.g., due to drastic changes in pH during experiments), we applied the treatment protocol from Fig 2E on cells transfected with the cytosolic or the peroxisomal GECI acceptor in the absence of donor or Ca\textsuperscript{2+}-binding site. Neither histamine addition nor addition of 1 mM Ca\textsuperscript{2+} showed signal change. We detected, however, mild photobleaching over time (Fig 2F).

When we treated HeLa cells expressing D3cpV-px according to this protocol, we observed two peaks (Fig 2G). Histamine addition resulted in a steep and fast increase in intraperoxisomal Ca\textsuperscript{2+} based on depletion of the ER. Addition of extracellular Ca\textsuperscript{2+} resulted in more gradual increase and gradual return to basal levels (Fig 2G).

For the interpretation of absolute peroxisomal Ca\textsuperscript{2+} concentrations and their comparison with the cytosolic concentrations we performed in situ titration experiments. The results were fit into the one-site binding model with Hill coefficient (Palmer et al, 2006; Park & Palmer, 2015) (Fig 2H). We found the K\textsubscript{a} of D3cpV to be 0.47 µM, which is very close to the in vitro value 0.6 µM. The K\textsubscript{a} of D3cpV-px was 1.1 µM and only slightly higher than the cytosolic. Using the measurements with D3cpV-px, the known properties of the sensor and the measured K\textsubscript{a} values for D3cpV-px in our experimental settings, we calculated the absolute Ca\textsuperscript{2+} concentration (Fig 2I) applying the formula described by Palmer and Tsien (2006). We find that under basal conditions, Ca\textsuperscript{2+} level in peroxisomes is around 600 nM and it rises upon near-physiological stimulation with histamine up to 2.4 µM Ca\textsuperscript{2+} (Fig 2I). The Ca\textsuperscript{2+} dynamics in peroxisomes measured with D3cpV-px was reproduced by pericam-px: a larger peak is observed after ER-store depletion and a smaller one after extracellular Ca\textsuperscript{2+} addition. The observed ratio curve from pericam-px largely resembles that from D3cpV-px. Because pericam has a reported in vitro K\textsubscript{a} value of 1.7 µM and covers higher Ca\textsuperscript{2+} concentrations, the observed result confirms the upper limit of peroxisomal Ca\textsuperscript{2+} and the range of Ca\textsuperscript{2+} between 0.6 and 2.4 µM (Fig 2K). For better consistency and comparability of the results, and because pericam is described as more pH sensitive than D3cpV (Nagai et al, 2001), we decided to perform all further experiments with D3cpV-px.

To confirm that the response in our experiments is due to the immediate increase in Ca\textsuperscript{2+} concentration, and to be able to directly compare peroxisomal Ca\textsuperscript{2+} handling with that of the cytosol, cells were co-transfected with D3cpV-px and the mApple-based cytosolic Ca\textsuperscript{2+} sensor R-GECO1, which increases in intensity when binding Ca\textsuperscript{2+} (Zhao et al, 2011). A large increase in the red signal from R-GECO1 was observed upon both ER-store depletion and addition of extracellular Ca\textsuperscript{2+} (blue curve in Fig 2L). Although the GECIs used for the measurement in two compartments have different properties that can result in differences in their kinetics, peroxisomes largely follow the Ca\textsuperscript{2+} changes in the cytosol. Interestingly, there is little or no delay between signal increase in cytosol and peroxisomes when stimulated with histamine, and the post-stimulation decline is more gradual and prolonged in peroxisomes compared with the cytosol, indicating the existence of a possible barrier or gate that can be saturated (Fig 2M).

To compare peroxisomal Ca\textsuperscript{2+} levels at rest and under stimulation with that of cytosol and mitochondria, cells were transfected with D3cpV sensors targeting specifically these compartments. FRET ratio was assessed as a direct indicator of Ca\textsuperscript{2+} concentration (Fig 3). All three compartments showed two peaks: one after ER-store depletion with histamine, and another after extracellular Ca\textsuperscript{2+} addition and PM-based uptake (Fig 3A).

The basal levels of Ca\textsuperscript{2+} in mitochondria and peroxisomes detected with this sensor were comparable and significantly higher than that in the cytosol (typically >100 nM, Paupe & Prudent, 2018) in
the current settings (Fig 3B). Furthermore, the increase in Ca^{2+} in peroxisomes upon intracellular store depletion with 100 μM histamine was significantly lower than the increase in the cytosol or mitochondria (Fig 3C). The Ca^{2+} increase rate in peroxisomes was more than twice lower than in cytosol or mitochondria (Fig 3D), speaking against the hypothesis that peroxisomal Ca^{2+} is rising drastically upon stimulation as suggested before (Lasorsa et al., 2008). The addition of extracellular Ca^{2+} resulted in another peak in all three compartments (Fig 3E), evidencing that peroxisomes, like mitochondria, depend on the PM-based uptake. Altogether, this suggests that peroxisomes tend to follow Ca^{2+} dynamics of the cytosol.

**Peroxisomal Ca^{2+} is not regulated by the mitochondrial calcium uniporter (MCU) complex**

We examined the possible influence of mitochondrial Ca^{2+} uptake on peroxisomal Ca^{2+} by performing knockdown of the main component and pore forming part of the MCU complex (De Stefani et al., 2011) with siRNA (Fig 4). Knockdown efficiency assessed by qPCR was more than 90% (Fig 4A). A non-targeting siRNA (siCtrl) was used as a control. Ca^{2+} measurements with R-GECO-mito as a mitochondrial Ca^{2+} sensor showed reduced Ca^{2+} uptake in MCU knockdown after histamine addition compared with the control (Fig 4B). The significantly decreased Ca^{2+} uptake to mitochondria further confirms the reduction in MCU activity in the knockdown (Fig 4C). In same cells co-expressing D3cpV-px, peroxisomes responded to histamine addition with signal increase in both control and knockdown (Fig 4D). We observed no difference in the Ca^{2+} uptake to peroxisomes immediately after histamine treatment (Fig 4E). However, after the peak peroxisomal Ca^{2+} remained constant in MCU knockdown, whereas the signal decreased gradually in the control. The observed increase could be attributed to an additional Ca^{2+} load. Less Ca^{2+} enters mitochondria in the MCU knockdown and the excess could enter peroxisomes. Together these results suggest that MCU is not responsible for Ca^{2+} transport across the peroxisomal membrane but peroxisomes may function as Ca^{2+} buffering system that takes up excess Ca^{2+}. Moreover, these findings suggest that peroxisomal and mitochondrial Ca^{2+} homeostases are tightly interconnected.

**Peroxisomal Ca^{2+} in cardiomyocytes rises with cytosolic Ca^{2+} increase**

We next tested in neonatal rat cardiomyocytes (NRCMs) the hypothesis that Ca^{2+} can access cardiac peroxisomes. NRCMs are primary cells with a well-developed T-tubule system and serve as a model for electrophysiological studies on CMs (Soeller & Cannell, 1999; Morad & Zhang, 2017).

We adapted the chemical stimulation protocol for the CMs by reducing it to a single stimulation because the main source of Ca^{2+} in these cells is the ER. We used thapsigargin (Tg) to chemically...
stimulate the CMs (Fig 5A). To avoid measurement distortion by spontaneous contractile activity of CMs, cells were treated with 2,3-butanedione monoxime (BDM) (Gwathmey et al, 1991) before the experiment. As a proof of concept and for direct comparison, we performed the first round of measurements using the cytosol-localized Ca\(^{2+}\)-sensor D3cpV (Fig 5B–D). Comparison between Tg treatment and buffer alone (Fig 5B) demonstrated, as expected, no differences in the basal ratios (Fig 5C), but an increase in cytosolic Ca\(^{2+}\) upon Tg addition (Fig 5D).

To measure peroxisomal Ca\(^{2+}\) changes, we transfected NRCMs with D3cpV-px and compared Tg treatment with the untreated control group (Fig 5E). No offset of basal ratios between the two groups was present before treatment (Fig 5F). After the addition of Tg, a significant increase in cytosolic Ca\(^{2+}\) was observed (Fig 5G).

In the next set of experiments, we wanted to know if peroxisomes of human cardiac cells are able to take up Ca\(^{2+}\). To test this, human iPSCs created from fibroblasts of a healthy donor were differentiated into CMs using standardized protocols (Fig 5H). The possibility to generate hiPSCs from somatic cell sources and to direct their differentiation into cardiomyocytes, are able to take up Ca\(^{2+}\) upon intracellular Ca\(^{2+}\)-store depletion and cytosolic Ca\(^{2+}\) increase.

Peroxisomal Ca\(^{2+}\) oscillates in cardiomyocytes

In contrast to non-excitable cells, cell depolarization is the main stimulus for the initiation of Ca\(^{2+}\) signalling in CMs. The action potential depolarizes the cell membrane resulting in the activation of voltage-gated L-type Ca\(^{2+}\) channels (LTCC) in T-tubules (Chapman, 1979; Bootman et al, 2002). As a result, an initial small amount of Ca\(^{2+}\) enters the cell, activating RyRs on the sarcoplasmic reticulum membrane, resulting in Ca\(^{2+}\) release from the stores. This Ca\(^{2+}\)-induced Ca\(^{2+}\) release enables cardiac muscle contraction. During relaxation, SERCA and NCX (sodium-calcium exchanger) pump Ca\(^{2+}\) back out of the cells (Chapman, 2007).

We performed a series of stainings to visualize relative localisation of peroxisomes and D3cpV-px to the LTCC and RyR in hiPSC-CMs (Fig 6). Both, stainings with anti-Pex14 antibody and transfection with D3cpV-px revealed that peroxisomes are occasionally in contact with LTCC (Fig 6A). More often proximity of peroxisomes was detected to RyR in CMs (Fig 6B). These findings are in accordance with the knowledge that peroxisomes make contact sites with the ER (Costello et al, 2017; Hua et al, 2017).

To enable more physiological interpretation of Ca\(^{2+}\) entry to peroxisomes in a beat-to-beat manner in NRCMs, we field-stimulated the cells with 1 Hz frequency (Fig 7A–D). Under field stimulation, we observed rhythmic changes of Ca\(^{2+}\) level in the cytosol (Fig 7A). To quantify the amplitude of changes and link to the stimulation, we performed fast Fourier transformation (FFT) of the data (Fig 7B). Signal amplitude
Figure 5. Measurement of peroxisomal Ca²⁺ in cardiomyocytes.

(A) Experimental paradigm of Ca²⁺ measurement in excitable cells. The peak after thapsigargin (Tg) addition represents Ca²⁺ increase due to the sarcoplasmic/endoplasmic reticulum calcium ATPase inhibition and Ca²⁺ retention in the cytosol. (A, B) Cytosolic Ca²⁺ measurement in NRCMs following the experimental design in (A), n = 25 (Tg), 22 (control) from three experiments. Addition of Tg is compared with the addition of Tg-free buffer (control).

(B, C) Basal levels are not different before the treatment in (B).

(B, D) After Tg addition in (B) cytosolic Ca²⁺ increases.

(A, E) Peroxisomal Ca²⁺ measurement in NRCMs following the experimental design in (A). Addition of Tg is compared with the addition of Tg-free buffer (control), n = 20 (Tg), 31 (control) from three experiments.

(E, F) Basal levels of Ca²⁺ are not different before the treatment.

Sargsyan et al. https://doi.org/10.26508/lsa.202000987 vol 4 | no 9 | e202000987 8 of 15

Peroxisomes contribute to intracellular calcium dynamics  Sargsyan et al.
oscillations in the cytosol were rhythmic and corresponded to the stimulation frequency (Fig 7B).

To test peroxisomal response to electrical stimulation, NRCMs expressing D3cpV-px were paced at a frequency of 1 Hz (Fig 7C). Oscillations observed were smaller in amplitude and appeared less regular than the cytosolic responses. To identify the frequency domain of these oscillations we performed FFT (Fig 7D). The extracted pattern showed amplitude changes at 1 Hz, suggesting that peroxisomes take up Ca^{2+} in beat-to-beat manner. Together, our results suggest that peroxisomal Ca^{2+} in CMs is dependent on excitation-contraction process.

Figure 6. Relative localisation of peroxisomes and Ca^{2+} channels in human induced pluripotent stem cell-CMs.

Human-induced pluripotent stem cell-CMs were either transfected with D3cpV-px (left panels) or stained with anti-Pex14 (right panels) as a peroxisomal marker. (A) Representative images from staining of L-type Ca^{2+} channel (LTCC) show occasional proximity of peroxisomes and LTCC. (B) Representative images from staining of ryanodine receptor (RyR2) show occasional yet more often contact of peroxisomes with the RyR2 than with LTCC. DAPI is shown in blue. Scale bar 5 μm.

Peroxisomes contribute to intracellular calcium dynamics Sargsyan et al. https://doi.org/10.26508/lsa.202000987 vol 4 | no 9 | e202000987

Data presented as means from three independent experiments. (C, D, F, G, L, M, O, P) Unpaired t test was used for the statistical analysis. ****P < 0.0001, Tukey’s box plots.
Discussion

Peroxisomes are metabolically highly active organelles in need of communication with other cellular compartments (Sargsyan & Thoms, 2020). ROS signalling and homeostasis are central to the participation of peroxisomes in signalling pathways (Lismont et al., 2019). In the present work, we focused on Ca²⁺ dynamics of peroxisomes as one of the major signalling molecules in the cell. We demonstrate that Ca²⁺ can enter peroxisomes of HeLa cells both when ER-stores are depleted and when cytosolic Ca²⁺ increases after Ca²⁺ entry across the PM.

Two articles published in 2008 brought forth conflicting data on peroxisomal Ca²⁺. According to Drago et al. (2008), the basal level of Ca²⁺ in peroxisomes equals the cytosolic Ca²⁺ level, whereas Lasorsa et al. (2008) find peroxisomal Ca²⁺ to be 20 times higher than in the cytosol. Whereas Lasorsa et al. (2008) report rise of peroxisomal Ca²⁺ up to 100 μM using an aequorin-based sensor, Drago et al. (2008) suggest slow increase when cytosolic Ca²⁺ rises. Each of the groups used a single yet different technique. These differences in the results can be partially attributed to the different measurement methods and the cell types used. Aequorin imaging requires long incubation times and cell population-based analysis that can be disadvantageous when measuring Ca²⁺ in intracellular organelles. In our experiments with HeLa cells, we found sixfold higher basal peroxisomal Ca²⁺ level than in the cytosol and increase up to 2.4 μM upon stimulation (Table 1). The range of the changes we report are based on the measurements with D3cpV-px and are supported by the measurement with pericam-px. Hence, we conclude that D3cpV-px can be used for measuring peroxisomal Ca²⁺ concentration in a broad variety of cell types.

Electron microscopic experiments on rodent hearts performed in the 1970s show that peroxisomes are closely associated with T-tubules and with junctional sarcoplasmic reticulum (Hicks & Fahimi, 1977). We show that peroxisomes in CMs localise more often in ER vicinity than to T-tubular system. The sarcoplasmic reticulum is an indispensable site for the excitation-contraction coupling and Ca²⁺ handling in myocytes (Flucher et al., 1994). The localisation of peroxisomes to these sites raises the question if cardiac peroxisomes react to Ca²⁺ oscillations on a beat-to-beat basis, and/or if they can buffer calcium. HiPSC-CMs provide a wide spectrum of possibilities in cardiac research ranging from drug screening to cardiac regeneration (Yoshida & Yamanaka, 2011). In addition, these cells have been especially used to study patient-specific disease models including arrhythmic disorders and cardiomyopathies demonstrating a robust correlation to the predicted phenotype (Borchert et al., 2017; Prondzynski et al., 2019). We report here that Ca²⁺ is entering peroxisomes upon intracellular Ca²⁺-store depletion in rat and human CMs. Because intracellular store depletion is the main source of Ca²⁺ in CMs in the process of excitation-contraction coupling, it can be hypothesized that peroxisomes take up Ca²⁺ also in beat-to-beat manner in these cells.

Indeed, measurement of peroxisomal Ca²⁺ in CMs with FRET sensors in field stimulation confirms that peroxisomal Ca²⁺ increases in beat-to-beat manner. This suggests that peroxisomes may participate in excitation-contraction processes. The exact role of peroxisomes here is the matter of future research. Furthermore, the experimental
protocols with chemical stimuli developed here can be applied to study peroxisomal Ca\(^{2+}\) in other cell types such as neurons.

We found that basal peroxisomal Ca\(^{2+}\) levels are higher than cytosolic levels. There are two major ways of generating this Ca\(^{2+}\) gradient on the two sides of the membrane. One option could be the energy-dependent uptake mechanism, such as SERCA for the ER (Clapham, 2007). We are, however, not aware of any data that can support this model. The second option may be locally high Ca\(^{2+}\) concentration at the entry site that would allow more direct channeling of Ca\(^{2+}\) (from the ER) into the peroxisomes resulting in relatively high peroxisomal Ca\(^{2+}\). This second mechanism is known from the mitochondrial Ca\(^{2+}\) handling, where ER–mitochondria contact sites with tethering proteins generate microdomain with locally high Ca\(^{2+}\) concentration (Hirabayashi et al, 2017). As a result, Ca\(^{2+}\) entry to mitochondria follows the Ca\(^{2+}\) gradient but mitochondrial Ca\(^{2+}\) is higher than the cytosolic Ca\(^{2+}\). For the plausibility of the second option for peroxisomes, we speak the existence of ER–peroxisome contact sites (Costello et al, 2017; Hua et al, 2017). Therefore, we propose a hypothetical model of this mechanism (Fig 8), which, if true, will kick-start the search for the molecular identity of its components.

Although peroxisomal Ca\(^{2+}\) levels are higher than cytosolic Ca\(^{2+}\) levels, peroxisomes are unlikely to store significant amounts of Ca\(^{2+}\) under normal conditions, and they themselves take up Ca\(^{2+}\) when intracellular stores are depleted. Under specific conditions, like apoptosis or oxidative stress, the situation may change, however. We observe gradual peroxisomal Ca\(^{2+}\) increase in the case of MCU knockdown. This provides the first hint that under specific conditions peroxisomes may function as additional Ca\(^{2+}\) buffer and take up excessive Ca\(^{2+}\) that may harm the cells. We show that the rise of peroxisomal Ca\(^{2+}\) after histamine stimulation is not delayed and largely follows the cytosolic Ca\(^{2+}\). Although there could be a delay due to the binding and conformational changes of GECIs needed before the detection of the increase in the FRET signal, the range of this delay is less than milliseconds and cannot be seen in the experiments described here. We conclude that peroxisomes respond to cytosolic Ca\(^{2+}\) because we only found concordant changes of Ca\(^{2+}\) concentration in these two compartments.

The question of the cellular function and potential targets of peroxisomal Ca\(^{2+}\) is still open. One of the roles of Ca\(^{2+}\) could be the regulation of peroxisomal processes. On the other hand, metabolic processes themselves may regulate Ca\(^{2+}\) uptake to organelles, as known from mitochondria (Nemani et al, 2020). A mutual regulation of metabolic pathways or ROS production localised to peroxisomes can be suggested based on the fact that Ca\(^{2+}\) channel blockers nifedipine and diltiazem have suppressive effects on peroxisomal enzymes (Watanabe & Suga, 1988). Peroxisome proliferator-activated receptors system may be the connecting point between the metabolic processes, ROS, peroxisome abundance, and cellular Ca\(^{2+}\) homeostasis (Colasante et al, 2015).

Some catalases from plant but not mammalian catalases can bind Ca\(^{2+}\) (Yang & Poovaiah, 2002). Currently, there are no peroxisomal processes known in mammals that would directly depend on Ca\(^{2+}\). Peroxisomes, however, could serve as an additional cytosolic buffer for Ca\(^{2+}\) to take up an excessive excess of cytosolic Ca\(^{2+}\) and release it slowly. Based on the findings of this study that the Ca\(^{2+}\) concentration in the peroxisome is higher than in the cytosol, it could be that peroxisomes may also serve as additional Ca\(^{2+}\) source for the cytosol in extreme situations. The buffering function of peroxisomes may thus be important in the pathogenesis of arrhythmias.

### Materials and Methods

#### DNA constructs

D3cpV-px (PST 1738) was generated from (pcDNA-)D3cpV (kind gift from A Palmer and R Tsien [Palmer et al, 2006]) by amplifying an insert with OST 1599 (GGCGATCGATGTTGACCC AAGTAAACTAGTAGAGCT TGAAGAG) and OST 1600 (GGCGGAATTC TTAGAGCTTC GATTTCAGAC TTCTCTCGA) primers. The product was then reinserted into D3cpV using Clal and EcoRI restriction sites. (pcDNA-)4mtD3cpV was a kind gift from A Palmer and R Tsien (Palmer et al, 2006) (#36324; Addgene). D1cpV-px (PST 2169) was generated from the (pcDNA-)D1cpV (Palmer et al, 2004) (#37479; Addgene) by amplifying an insert with oligonucleotide OST 2001 (GGCGCGATCC CATGTTGACG AAGGGC) and OST 2002 (GGCGGAATTC TTAGAGCTTC GATTTCAGAC TTCTCTCGA) primers. The product was then reinserted into D1cpV using EcoRI and BamHI restriction sites. Pericam-px (PST 2170) was generated from ratiometric pericam (for mitochondria) (Nagai et al, 2001) by amplifying an insert with OST 2003 (GGCGCGATCC CATGTTGACG AAGGGC) and OST 2002 (GGCGGAATTC TTAGAGCTTC GATTTCAGAC TTCTCTCGA) primers. The product was then reinserted into D1cpV using EcoRI and BamHI restriction sites. Pericam-px (PST 2170) was generated from ratiometric pericam (for mitochondria) (Nagai et al, 2001) by amplifying an insert with OST 2003 (GGCGCGATCC CATGTTGACG AAGGGC) and OST 2002 (GGCGGAATTC TTAGAGCTTC GATTTCAGAC TTCTCTCGA) primers. The product was then reinserted into ratiometric pericam using EcoRI and HindIII restriction sites. (CMV-)R-GECO1 and mito-R-GECO (#46021; Addgene) were kind gifts from R Campbell (Zhao et al, 2011). EYFP (Clontech) and Venus-PTS1 (PST1226) were used as the acceptor control.
For cloning of pVENUS-PT5 (PST1226), oligonucleotides OST801
(CACCGGTGTC TATGAGAGCT CAAATCTGAA GCCTCTAG) and OST802
(CATAGAGCTT AGTCTGAGCT TCTATGAGC AGGGGTG) encoding the C-
terminal decapeptide ACOX3 were annealed and cloned into the pENTR/D-TOPO cloning vector, yielding pENTR-ACOX3dp (PST1209). The resulting insert was transferred to pDEST-Venus using the Gateway cloning system.

**Cells, cell culture, and immunofluorescence**

HeLa cells were cultured in low glucose DMEM medium (Biochrom) supplemented with 1% Pen/Strep (100 U/ml penicillin and 100 μg/ml streptomycin), 1% (wt/vol) glutamine, and 10% (vol/vol) FCS in 5% CO2 at 37°C. For immunofluorescence analysis, cells were fixed with 4% paraformaldehyde for 30 min, and permeabilized using 1% Triton X-100 in PBS for 10 min. After blocking for 30 min with 10% BSA in PBS (blocking buffer) at 37°C, antigens were labelled with primary antibodies at room temperature for 1 h. Rabbit anti-P-PEX14 (ProteinTech) and mouse anti-PMP70 (Sigma-Aldrich) primary antibody dilution in blocking buffer was 1:500, and 1200 for mouse anti-RyR (Invitrogen) and goat anti-LTCC (Santa Cruz). Labelling with the secondary antibodies conjugated to Cy3 (Thermo Fisher Scientific), Alexa Fluor 488 (Life Technologies), Alexa Fluor 633 (Invitrogen), or Alexa Fluor 647 (Jackson immunoResearch) was done for 1 h (1:500). Cover slips were mounted with ProLong Gold mounting medium with or without DAPI (Thermo Fisher Scientific). Images were taken with Axio Observer Z1 (equipped Zeiss Colibri 7 and with 63× oil Fluar) and deconvoluted. Co-localisation analysis was performed with Fiji (http://fiji.sc/) according to ImageJ User Guide. Mandor’s colocalisation coefficient was measured after applying MaxEntropy thresholding on images.

NRCMs were isolated from newborn rats. Briefly, after the rats were euthanized, hearts were removed from the thoracic cavity, homogenized mechanically and digested in 1 mg/ml collagenase type II containing calcium- and magnesium-free PBS at 37°C with magnetic stirring. Supernatant was taken every 20 min and transferred to DMEM medium supplemented with Glutamax (Thermo Fisher Scientific), 10% FCS and 1% Pen/Strep. Cells were then centrifuged, the cell pellet resuspended in fresh medium and transferred to a Petri dish for 45 min (37°C and 5% CO2). The fibroblasts adhered and NRCMs remained in the supernatant. NRCMs were then seeded on glass cover slips covered by Geltrex (Thermo Fisher Scientific) and deconvoluted. Co-localisation analysis was performed with Fiji (http://fiji.sc/) according to ImageJ User Guide. Mandor’s colocalisation coefficient was measured after applying MaxEntropy thresholding on images.

Cells (200,000 for HeLa and hiPSC-CMs and 500,000 for NRCMs) were seeded on glass cover slips and transfected with sense plasmids using Effectene (Qiagen) (HeLa) or Lipofectamine LTX Reagent (Thermo Fisher Scientific) (hiPSC-CMs and NRCMs) according to the manufacturers’ instructions. Cells were imaged using a Zeiss Observer D1 equipped with a EC-Plan Neofluar 40×/1.3 Oil Ph3 objective; AxioCam 702 mono and LED system Colibri; Zeiss) or Axio Observer D1 equipped with a 40×/1.3 Oil Fluor objective, Zeiss Axiocam 702, Definite Focus 2 and Zeiss Colibri 7) at 337°C in a Ca2+-free imaging buffer (145 mM NaCl, 4 mM KCl, 10 mM Hepes, 10 mM glucose, 2 mM MgCl2, and 1 mM EGTA, pH 7.4 at 37°C) 24 h (HeLa and NRCMs) or 48 h (hiPSC-CMs) after transfection. Where indicated, NRCMs were field-stimulated at 1 Hz with MyoPacer ES (IonOptix). Data were analysed with Axiovision (Zeiss) and ZEN (Zeiss) software.

**Ca2+ measurements**

Excitation 420 ± 20 and 505 ± 15 nm with emission filters 483 ± 16 and 542 ± 14 nm, or excitation 438 ± 12 and 508 ± 11 nm with emission filters 479 ± 20 and 544 ± 14 nm were used. For R-GECI measurements excitation was 550 ± 16 nm and emission 630 ± 46 nm. Where indicated, the concentration of Ca2+ in the imaging buffer was increased by 1 mM by doubling the buffer volume to the cells (e.g., during treatment with chemicals) by the addition of Ca2+-containing buffer (imaging buffer that contains 2 mM CaCl2 [pH 7.4, 37°C] instead of EGTA).

The apparent dissociation constant Kd value in the experimental setup was determined based on the titration protocol described for cytosolic GECI (Park & Palmer, 2015) with some modifications. Briefly, cells were washed with Ca2+-, Mg2+-, and EGTA-free buffer (pH 7.2) and incubated in Ca2+- and Mg2+-free buffer (pH 7.2) containing 3 mM EGTA and 5 mM ionomycin until the FRET signal reached

**siRNA-mediated protein knockdown and qPCR**

Transient knockdown was generated using siRNA from Microsynth (siMCU_1 sense: 5′-CUG GCC AUU GUA AUC UUA ACA dTdT-3′; siMCU_2 sense: 5′-CUU GCC UGU AUU GUA ACA dTdT-3′; siCtrl sense: 5′-UUC GGA CGU GUC ACG U- dTdT 3′). 3 million cells were transfected by nucleofection (Amaxa Nucleofector; Lonza GmbH) using the SE Cell Line Kit (P44XC-1012) according to manufacturer’s instructions with 4 μl of a 20 μM siRNA stock solution (for MCU using 2 μl siMCU_1 and 2 μl siMCU_2). All measurements were performed 72 h after transfection and the knockdown efficiency was confirmed using the same cells for qPCR.
Peroxisomes contribute to intracellular calcium dynamics  Sargsyan et al.

Supplementary Information

Supplementary Information is available at https://doi.org/10.26508/lsa.202000987.

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Author Contributions

Y Sargsyan: formal analysis, investigation, visualization, and writing—original draft, review, and editing.
U Bickmeyer: investigation and writing—review and editing.
C J Ghirardi: investigation.
K Streckfuss-Bomeke: resources, supervision, and writing—original draft.
I Bogeski: resources, supervision, and writing—original draft.
S Thoms: conceptualization, resources, formal analysis, supervision, funding acquisition, visualization, project administration, and writing—original draft, review, and editing.

Conflict of Interest Statement

The authors declare that they have no conflict of interest.

References


Peroxisomes contribute to intracellular calcium dynamics

Sorgsyan et al.


