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Permalink
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Journal
eLife, 2015(4)

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Publication Date
2015-01-15

DOI
10.7554/eLife.04801

Peer reviewed
Mitochondrial Ca\(^{2+}\) uptake by the voltage-dependent anion channel 2 regulates cardiac rhythmicity

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Abstract

Tightly regulated Ca\(^{2+}\) homeostasis is a prerequisite for proper cardiac function. To dissect the regulatory network of cardiac Ca\(^{2+}\) handling, we performed a chemical suppressor screen on zebrafish tremblor embryos, which suffer from Ca\(^{2+}\) extrusion defects. Efsevin was identified based on its potent activity to restore coordinated contractions in tremblor. We show that efsevin binds to VDAC2, potentiates mitochondrial Ca\(^{2+}\) uptake and accelerates the transfer of Ca\(^{2+}\) from intracellular stores into mitochondria. In cardiomyocytes, efsevin restricts the temporal and spatial boundaries of Ca\(^{2+}\) sparks and thereby inhibits Ca\(^{2+}\) overload-induced erratic Ca\(^{2+}\) waves and irregular contractions. We further show that overexpression of VDAC2 recapitulates the suppressive effect of efsevin on tremblor embryos whereas VDAC2 deficiency attenuates efsevin’s rescue effect and that VDAC2 functions synergistically with MCU to suppress cardiac fibrillation in tremblor. Together, these findings demonstrate a critical modulatory role for VDAC2-dependent mitochondrial Ca\(^{2+}\) uptake in the regulation of cardiac rhythmicity.

Introduction

During development, well-orchestrated cellular processes guide cells from diverse lineages to integrate into the primitive heart tube and establish rhythmic and coordinated contractions. While many genes and pathways important for cardiac morphogenesis have been identified, molecular
**eLife digest** The heart is a large muscle that pumps blood around the body by maintaining a regular rhythm of contraction and relaxation. If the heart loses this regular rhythm it works less efficiently, which can lead to life-threatening conditions.

Regular heart rhythms are maintained by changes in the concentration of calcium ions in the cytoplasm of the heart muscle cells. These changes are synchronised so that the heart cells contract in a controlled manner. In each cell, a contraction begins when calcium ions from outside the cell enter the cytoplasm by passing through a channel protein in the membrane that surrounds the cell. This triggers the release of even more calcium ions into the cytoplasm from stores within the cell. For the cells to relax, the calcium ions must then be pumped out of the cytoplasm to lower the calcium ion concentration back to the original level.

Shimizu et al. studied a zebrafish mutant—called tremblor—that has irregular heart rhythms because its heart muscle cells are unable to efficiently remove calcium ions from the cytoplasm. Embryos of the tremblor mutant were treated with a wide variety of chemical compounds with the aim of finding some that could correct the heart defect.

A compound called efsevin restores regular heart rhythms in tremblor mutants. Efsevin binds to a pump protein called VDAC2, which is found in compartments called mitochondria within the cell. Although mitochondria are best known for their role in supplying energy for the cell, they also act as internal stores for calcium. By binding to VDAC2, efsevin increases the rate at which calcium ions are pumped from the cytoplasm into the mitochondria. This restores rhythmic calcium ion cycling in the cytoplasm and enables the heart muscle cells to develop regular rhythms of contraction and relaxation. Increasing the levels of VDAC2 or another similar calcium ion pump protein in the heart cells can also restore a regular heart rhythm.

Efsevin can also correct irregular heart rhythms in human and mouse heart muscle cells, therefore the new role for mitochondria in controlling heart rhythms found by Shimizu et al. appears to be shared in other animals. The experiments have also identified the VDAC family of proteins as potential new targets for drug therapies to treat people with irregular heart rhythms.

DOI: 10.7554/eLife.04801.002

The mechanisms governing embryonic cardiac rhythmicity are poorly understood. The findings that Ca\(^{2+}\) waves traveling across the heart soon after the formation of the primitive heart tube (Chi et al., 2002) and that loss of function of key Ca\(^{2+}\) regulatory proteins, such as the L-type Ca\(^{2+}\) channel, Na/K-ATPase and sodium-calcium exchanger 1 (NCX1), severely impairs normal cardiac function (Rottbauer et al., 2001; Shu et al., 2003; Ebert et al., 2005; Langenbacher et al., 2005), indicate an essential role for Ca\(^{2+}\) handling in the regulation of embryonic cardiac function.

Ca\(^{2+}\) homeostasis in cardiac muscle cells is tightly regulated at the temporal and spatial level by a subcellular network involving multiple proteins, pathways, and organelles. The release and reuptake of Ca\(^{2+}\) by the sarcoplasmic reticulum (SR), the largest Ca\(^{2+}\) store in cardiomyocytes, constitutes the primary mechanism governing the contraction and relaxation of the heart. Ca\(^{2+}\) influx after activation of the L-type Ca\(^{2+}\) channel in the plasma membrane induces the release of Ca\(^{2+}\) from the SR via ryanodine receptor (RyR) channels, which leads to an increase of the intracellular Ca\(^{2+}\) concentration and cardiac contraction. During diastolic relaxation, Ca\(^{2+}\) is transferred back into the SR by the SR Ca\(^{2+}\) pump or extruded from the cell through NCX1. Defects in cardiac Ca\(^{2+}\) handling and Ca\(^{2+}\) overload, for example during cardiac ischemia/reperfusion or in long QT syndrome, are well known causes of contractile dysfunction and many types of arrhythmias including early and delayed afterdepolarizations and Torsade des pointes (Bers, 2002; Choi et al., 2002; Yano et al., 2008; Greiser et al., 2011).

Ca\(^{2+}\) crosstalk between mitochondria and ER/SR has been noted in many cell types and the voltage-dependent anion channel (VDAC) and the mitochondrial Ca\(^{2+}\) uniporter (MCU) serve as primary routes for Ca\(^{2+}\) entry through the outer and inner mitochondrial membranes, respectively (Rapizzi et al., 2002; Bathori et al., 2006; Shoshan-Barmatz et al., 2010; Baughman et al., 2011; De Stefani et al., 2011). In the heart, mitochondria are tethered to the SR and are located in close proximity to Ca\(^{2+}\) release sites (García-Pérez et al., 2008; Boncompagni et al., 2009; Hayashi et al., 2009). This subcellular architecture exposes the mitochondria near the Ca\(^{2+}\) release sites to a high local Ca\(^{2+}\) concentration.
that is sufficient to overcome the low Ca\textsuperscript{2+} affinity of MCU and facilitates Ca\textsuperscript{2+} crosstalk between SR and mitochondria (García-Pérez et al., 2008; Dorn and Scorrano, 2010; Kohlhaas and Maack, 2013). Increase of the mitochondrial Ca\textsuperscript{2+} concentration enhances energy production during higher workload and dysregulation of SR-mitochondrial Ca\textsuperscript{2+} signaling results in energetic deficits and oxidative stress in the heart and may trigger programmed cell death (Brandes and Bers, 1997; Maack et al., 2006; Kohlhaas and Maack, 2013). However, whether SR-mitochondrial Ca\textsuperscript{2+} crosstalk also contributes significantly to cardiac Ca\textsuperscript{2+} signaling during excitation-contraction coupling requires further investigation.

In zebrafish, the tremblor (tre) locus encodes a cardiac-specific isoform of the Na\textsuperscript{+}/Ca\textsuperscript{2+} exchanger 1, NCX1h (also known as slc8a1a) (Ebert et al., 2005; Langenbacher et al., 2005). The tre mutant hearts...
lack rhythmic Ca\(^{2+}\) transients and display chaotic Ca\(^{2+}\) signals in the myocardium leading to unsynchronized contractions resembling cardiac fibrillation (Langenbacher et al., 2005). In this study, we used tre as an animal model for aberrant Ca\(^{2+}\) handling-induced cardiac dysfunction and took a chemical genetic approach to dissect the Ca\(^{2+}\) regulatory network important for maintaining cardiac rhythmicity. A synthetic compound named efsevin was identified from a suppressor screen due to its potent ability to restore coordinated contractions in tre. Using biochemical and genetic approaches we show that efsevin interacts with VDAC2 and potentiates its mitochondrial Ca\(^{2+}\) transporting activity and spatially and temporally modulates cytosolic Ca\(^{2+}\) signals in cardiomyocytes. The important role of mitochondrial Ca\(^{2+}\) uptake in regulating cardiac rhythmicity is further supported by the suppressive effect of VDAC2 and MCU overexpression on cardiac fibrillation in tre.

**Results and discussion**

**Identification of a chemical suppressor of tre cardiac dysfunction**

Homozygous tre mutant embryos suffer from Ca\(^{2+}\) extrusion defects and manifest chaotic cardiac contractions resembling fibrillation (Ebert et al., 2005; Langenbacher et al., 2005). To dissect the regulatory network of Ca\(^{2+}\) handling in cardiomyocytes and to identify mechanisms controlling embryonic cardiac rhythmicity, we screened the BioMol library and a collection of synthetic compounds for chemicals that are capable of restoring heartbeat either completely or partially in tre embryos. A dihydropyrrole carboxylic ester compound named efsevin was identified based on its ability to restore persistent and rhythmic cardiac contractions in tre mutant embryos in a dose-dependent manner (Figure 1A,E, and Videos 1–4). To validate the effect of efsevin, we assessed cardiac performance of wild type, tre and efsevin-treated tre embryos (Nguyen et al., 2009). Fractional shortening of efsevin treated tre mutant hearts was comparable to that of their wild type siblings and heart rate was restored to approximately 40% of that observed in controls (Figure 1B–D). Periodic local field potentials accompanying each heartbeat were detected in wild type and efsevin-treated tre embryos using a microelectrode array (Figure 1F–H). Furthermore, while only sporadic Ca\(^{2+}\) signals were detected in tre hearts, in vivo Ca\(^{2+}\) imaging revealed steady Ca\(^{2+}\) waves propagating through efsevin-treated tre hearts (Figure 1I, Videos 5–7), demonstrating that cardiomyocytes are functionally coupled and that efsevin treatment restores regular Ca\(^{2+}\) transients in tre hearts.
Efsevin suppresses Ca\textsuperscript{2+} overload-induced irregular contraction

We next examined whether efsevin could suppress aberrant Ca\textsuperscript{2+} homeostasis-induced arrhythmic responses in mammalian cardiomyocytes. Mouse embryonic stem cell-derived cardiomyocytes (mESC-CMs) establish a regular contraction pattern with rhythmic Ca\textsuperscript{2+} transients (Figure 2A,B,E,F). Mimicking Ca\textsuperscript{2+} overload by increasing extracellular Ca\textsuperscript{2+} levels was sufficient to disrupt normal Ca\textsuperscript{2+} cycling and induce irregular contractions in mESC-CMs (Figure 2C,E,F). Remarkably, efsevin treatment restored rhythmic Ca\textsuperscript{2+} transients and cardiac contractions in these cells (Figure 2D–F). Similar effect was observed in human embryonic stem cell-derived cardiomyocytes (hESC-CMs) (Figure 2G). Together, these findings suggest that efsevin targets a conserved Ca\textsuperscript{2+} regulatory mechanism critical for maintaining rhythmic cardiac contraction in fish, mice and humans.

VDAC2 mediates the suppressive effect of efsevin on tre

To identify the protein target of efsevin, we generated a N-Boc-protected 2-aminoethoxyethoxyethylamine linker-attached efsevin (efsevin\textsuperscript{L}) (Figure 3A,C). This modified compound retained the activity of efsevin to restore cardiac contractions in ncnx1h deficient embryos (Figure 3B,D) and was used to create efsevin-conjugated agarose beads (efsevin\textsuperscript{LB}). A 32kD protein species was detected from zebrafish lysate due to its binding ability to efsevin\textsuperscript{LB} and OK-C125\textsuperscript{LB}, an active efsevin derivative conjugated to beads, but not to beads capped with ethanolamine alone or beads conjugated with an inactive efsevin analog (OK-C19\textsuperscript{LB}) (Figure 3A–E). Furthermore, preincubation of zebrafish lysate with excess efsevin prevented the 32kD protein from binding to efsevin\textsuperscript{LB} or OK-C125\textsuperscript{LB} (Figure 3E). Mass spectrometry analysis revealed that this 32kD band represents a zebrafish homologue of the mitochondrial voltage-dependent anion channel 2 (VDAC2) (Figure 3F and Figure 3—figure supplement 1).

VDAC2 is expressed in the developing zebrafish heart (Figure 4A), making it a good candidate for mediating efsevin’s effect on cardiac Ca\textsuperscript{2+} handling. To examine this possibility, we injected in vitro synthesized VDAC2 RNA into tre embryos and found that the majority of these embryos had coordinated cardiac contractions similar to those subjected to efsevin treatment (Figure 4B, Videos 8–11). In addition, we generated myl7:VDAC2 transgenic fish in which VDAC2 expression can be induced in the heart by tebufenozide (TBF) (Figure 4C). Knocking down NCX1h in myl7:VDAC2 embryos results in chaotic cardiac movement similar to tre. Like efsevin treatment, induction of VDAC2 expression by TBF treatment restored coordinated and rhythmic contractions in myl7:VDAC2;NCX1h MO hearts (Figure 4D, Videos 12,13). Conversely, knocking down VDAC2 in tre hearts attenuated the suppressive effect of efsevin (Figure 4E, Videos 14–16). Furthermore, we generated VDAC2 null embryos by the Zinc Finger Nuclease gene targeting approach (Figure 4G). Similar to that observed in morpholino knockdown embryos, homozygous VDAC2\textsuperscript{LA2256} embryos do not exhibit noticeable morphological changes (Figure 4F, Videos 17,18).
defects, but the suppressive effect of efsevin was attenuated in homozygous VDAC2<sup>A2256</sup>; NCX1MO embryos (Figure 4F). These findings demonstrate that VDAC2 is a major mediator for efsevin’s effect on ncx1h deficient hearts.

**VDAC2-dependent effect of efsevin on mitochondrial Ca<sup>2+</sup> uptake**

VDAC is an abundant channel located on the outer mitochondrial membrane serving as a primary passageway for metabolites and ions (Figure 5A) (Rapizzi et al., 2002; Bathori et al., 2006; Shoshan-Barmatz et al., 2010). At its close state, VDAC favours Ca<sup>2+</sup> flux (Tan and Colombini, 2007). To examine whether efsevin would modulate mitochondrial Ca<sup>2+</sup> uptake via VDAC2, we transfected HeLa cells with VDAC2. We noted increased mitochondrial Ca<sup>2+</sup> uptake in permeabilized VDAC2 transfected and efsevin-treated cells after the addition of Ca<sup>2+</sup> and the combined treatment further enhanced mitochondrial Ca<sup>2+</sup> levels (Figure 5B).

Mitochondria are located in close proximity to Ca<sup>2+</sup> release sites of the ER/SR and an extensive crosstalk between the two organelles exists (García-Pérez et al., 2008; Hayashi et al., 2009; Brown and O’Rourke, 2010; Dorn and Scorrano, 2010; Kohlhaas and Maack, 2013). We examined whether Ca<sup>2+</sup> released from intracellular stores could be locally transported into mitochondria through VDAC2 in VDAC1/VDAC3 double knock-out (V1/V3DKO) MEFs where VDAC2 is the only VDAC isoform being expressed (Roy et al., 2009a). While treatments with ATP, an IP3-linked agonist, and thapsigargin, a SERCA inhibitor, stimulated similar global cytoplasmic [Ca<sup>2+</sup>] elevation in intact cells, only ATP induced a rapid mitochondrial matrix [Ca<sup>2+</sup>] rise (Figure 5—figure supplement 1). This finding is consistent with observations obtained in other cell types (Rizzuto et al., 1994; Hajnóczky et al., 1995) and suggests that Ca<sup>2+</sup> was locally transferred from IP3 receptors to mitochondria through VDAC2 at the close ER-mitochondrial associations. We next investigated whether this process could be modulated by efsevin. In permeabilized V1/V3DKO MEFs, treatment with efsevin increased the amount of Ca<sup>2+</sup> transferred into mitochondria during IP<sub>3</sub>-induced Ca<sup>2+</sup> release (Figure 5C). Also, in intact V1/V3 DKO MEFs, efsevin accelerated the transfer of Ca<sup>2+</sup> released from intracellular stores into mitochondria during stimulation with ATP (Figure 5D,E).

**Efsevin modulates Ca<sup>2+</sup> sparks and suppresses erratic Ca<sup>2+</sup> waves in cardiomyocytes**

We next examined the effect of efsevin on cytosolic Ca<sup>2+</sup> signals in isolated adult murine cardiomyocytes. We found that efsevin treatment induced faster inactivation kinetics without affecting the...
amplitude or time to peak of paced Ca\(^{2+}\) transients (Figure 6A). Similarly, efsevin treatment did not significantly alter the frequency, amplitude or Ca\(^{2+}\) release flux of spontaneous Ca\(^{2+}\) sparks, local Ca\(^{2+}\) release events, but accelerated the decay phase resulting in sparks with a shorter duration and a narrower width (Figure 6B). These results indicate that by activating mitochondrial Ca\(^{2+}\) uptake, efsevin accelerates Ca\(^{2+}\) removal from the cytosol in cardiomyocytes and thereby restricts local cytosolic Ca\(^{2+}\) sparks to a narrower domain for a shorter period of time without affecting SR Ca\(^{2+}\) load or RyR Ca\(^{2+}\) release. Under conditions of Ca\(^{2+}\) overload, single Ca\(^{2+}\) sparks can trigger opening of neighbouring Ca\(^{2+}\) release units and thus induce the formation of erratic Ca\(^{2+}\) waves (Figure 6C). Efsevin treatment significantly reduced the number of propagating Ca\(^{2+}\) waves in a dosage-dependent manner (Figure 6C,D), demonstrating a potent suppressive effect of efsevin on the propagation of Ca\(^{2+}\) overload-induced Ca\(^{2+}\) waves and suggesting that efsevin could serve as a pharmacological tool to manipulate local Ca\(^{2+}\) signals.
Mitochondrial Ca\textsuperscript{2+} uptake modulates embryonic cardiac rhythmicity

We hypothesize that efsevin treatment/VDAC2 overexpression suppresses aberrant Ca\textsuperscript{2+} handling-associated arrhythmic cardiac contractions by buffering excess Ca\textsuperscript{2+} into mitochondria. This hypothesis predicts that activating other mitochondrial Ca\textsuperscript{2+} uptake molecules would likewise restore coordinated contractions in tre. To test this model, we cloned zebrafish MCU and MICU1, an inner mitochondrial membrane Ca\textsuperscript{2+} transporter and its regulator (Perochii et al., 2010; Baughman et al., 2011; De Stefani et al., 2011; Mallilankaraman et al., 2012; Csordas et al., 2013). In situ hybridization showed that MCU and MICU1 were expressed in the developing zebrafish heart (Figure 7A) and their expression levels were comparable between the wild type and tre hearts (Figure 7—figure supplement 1). Overexpression of MCU restored coordinated contractions in tre, akin to what was observed with VDAC2 (Figure 7B). In addition, tre embryos injected with suboptimal concentrations of MCU or VDAC2 had a fibrillating heart, but embryos receiving both VDAC2 and MCU at the suboptimal concentration manifested coordinated contractions (Figure 7C), demonstrating a synergistic effect of these proteins. Furthermore, overexpression of MCU failed to suppress the tre phenotype in the absence of VDAC2 activity and VDAC2 could not restore coordinated contractions in tre without functional MCU (Figure 7B,D). Similar results were observed by manipulating MICU1 activity (Figure 7E,F). Together, these findings indicate that mitochondrial Ca\textsuperscript{2+} uptake mechanisms on outer and inner mitochondrial membranes act cooperatively to regulate cardiac rhythmicity.

Conclusion

In summary, we conducted a chemical suppressor screen in zebrafish to dissect the regulatory network critical for maintaining rhythmic cardiac contractions and to identify mechanisms underlying aberrant
Ca\textsuperscript{2+} handling-induced cardiac dysfunction. We show that activation of VDAC2 through overexpression or efsevin treatment potently restores rhythmic contractions in NCX1h deficient zebrafish hearts and effectively suppresses Ca\textsuperscript{2+} overload-induced arrhythmogenic Ca\textsuperscript{2+} events and irregular contractions in mouse and human cardiomyocytes. We provide evidence that potentiating VDAC2 activity enhances mitochondrial Ca\textsuperscript{2+} uptake, accelerates Ca\textsuperscript{2+} transfer from intracellular stores into mitochondria and spatially and temporally restricts single Ca\textsuperscript{2+} sparks in cardiomyocytes. The crucial role of mitochondria in the regulation of cardiac rhythmicity is further supported by the findings that VDAC2 functions in concert with MCU; these genes have a strong synergistic effect on suppressing cardiac fibrillation and loss of function of either gene abrogates the rescue effect of the other in tre.

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Video 8. This video shows a heart of a wild-type zebrafish embryo at 1 dpf. Robust rhythmic contractions can be observed in atrium and ventricle.

DOI: 10.7554/eLife.04801.015
The regulatory roles of mitochondrial Ca\(^{2+}\) in cardiac metabolism, cell survival and fate have been studied extensively (Brown and O'Rourke, 2010; Dorn and Scorrano, 2010; Doenst et al., 2013; Kasahara et al., 2013; Kohlhaas and Maack, 2013; Luo and Anderson, 2013). Our study provides genetic and physiologic evidence supporting an additional role for mitochondria in regulating cardiac rhythmicity and reveals VDAC2 as a modulator of Ca\(^{2+}\) handling in cardiomyocytes. Our findings, together with recent reports of the physical interaction between VDAC2 and RyR2 (Min et al., 2012) and the close proximity of outer and inner mitochondrial membranes at the contact sites between the mitochondria and the SR (García-Pérez et al., 2011), suggest an intriguing model. We propose that mitochondria facilitate an efficient clearance mechanism in the Ca\(^{2+}\) microdomain, which modulates Ca\(^{2+}\) handling without affecting global Ca\(^{2+}\) signals in cardiomyocytes. In this model, VDAC facilitates mitochondrial Ca\(^{2+}\) uptake via MCU complex and thereby controls the duration and the diffusion of cytosolic Ca\(^{2+}\) near the Ca\(^{2+}\) release sites to ensure rhythmic cardiac contractions. This model is consistent with our observation that efsevin treatment induces faster inactivation kinetics of cytosolic Ca\(^{2+}\) transients without affecting the amplitude or the time to peak in cardiomyocytes and the reports that blocking mitochondrial Ca\(^{2+}\) uptake has little impact on cytosolic Ca\(^{2+}\) transients (Maack et al., 2006; Kohlhaas et al., 2010). Further support for this model comes from the observation of the Ca\(^{2+}\) peaks on the OMM (Drago et al., 2012) and the finding that down-regulating VDAC2 extends Ca\(^{2+}\) sparks (Subedi et al., 2011; Min et al., 2012) and that blocking mitochondrial Ca\(^{2+}\) uptake by Ru360 leads to an increased number of spontaneous propagating Ca\(^{2+}\) waves (Seguchi et al., 2005). Future studies on the kinetics of VDAC2-dependent mitochondrial Ca\(^{2+}\) uptake and exploring potential regulatory molecules for VDAC2 activity will provide insights into how the crosstalk between SR and mitochondria contributes to Ca\(^{2+}\) handling and cardiac rhythmicity.

Aberrant Ca\(^{2+}\) handling is associated with many cardiac dysfunctions including arrhythmia. Establishing animal models to study molecular mechanisms and develop new therapeutic strategies are therefore major preclinical needs. Our chemical suppressor screen identified a potent effect of efsevin and its biological target VDAC2 on manipulating cardiac Ca\(^{2+}\) handling and restoring regular cardiac contractions in fish and mouse and human cardiomyocytes. This success indicates that fundamental mechanisms regulating cardiac function are conserved among vertebrates despite the existence of species-specific features and suggests a new paradigm of using zebrafish cardiac disease models for the dissection of critical genetic pathways and the discovery of new therapeutic approaches. Future studies examining the effects of efsevin on other
arrhythmia models would further elucidate the potential for efsevin as a pharmacological tool to treat cardiac arrhythmia associated with aberrant Ca²⁺ handling.

Materials and methods

Zebrafish husbandry and transgenic lines

Zebrafish of the mutant line tremblor (tre₃₁₈²) were maintained and bred as described previously (Langenbacher et al., 2005). Transgenic lines, myl7: gCaMP4.1₋₋₋₋₋₋ and myl7:VDAC2₋₋₋₋₋₋ were created using the Tol2kit (Esengil et al., 2007; Kwan et al., 2007; Shindo et al., 2010). The VDAC2₋₋₋₋₋₋ was created using the zinc finger array OZ523 and OZ524 generated by the zebrafish Zinc Finger Consortium (Foley et al., 2009a, 2009b).

Molecular Biology

Full length VDAC2 cDNA was purchased from Open Biosystems (Huntsville, AL) and cloned into pCS2+ or pCS2+3XFLAG. Full length cDNA fragments of zebrafish MCU (Accession number: JX424822) and MICU1 (JX42823) were amplified from 2 dpf embryos and cloned into pCS2+. For mRNA synthesis, plasmids were linearized and mRNA was synthesized using the SP6 mMES-SAGE mMachine kit according to the manufacturer's manual (Ambion, Austin, TX.).

Zebrafish injections

VDAC2 mRNA and morpholino antisense oligos (5′-GGGAACGGCCATTTTATCTGTTAAA-3′) (Genetools, Philomath, OR) were injected into one-cell stage embryos collected from crosses of tre₃₁₈² heterozygotes. Cardiac performance was analyzed by visual inspection on 1 dpf. The tre mutant embryos were identified either by observing the fibrillation phenotype at 2–3 dpf or by genotyping as previously described (Langenbacher et al., 2005).

Chemical screen

Chemicals from a synthetic library (Castellano et al., 2007; Choi et al., 2011; Cruz et al., 2011) and from Biomol International LP (Farmingdale, NY) were screened for their ability to partially or completely restore persistent heartbeat in tre embryos. 12 embryos collected from crosses of tre₃₁₈² heterozygotes were raised in the presence of individual compounds at a concentration of 10 µM from 4 hpf (Choi et al., 2011). Cardiac function was analyzed by visual inspection at 1 and 2 dpf. The hearts of tre₃₁₈² embryos manifest a chaotic movement resembling cardiac fibrillation with intermittent contractions in rare occasion (Ebert et al., 2005; Langenbacher et al., 2005). Compounds that elicit persistent coordinated cardiac contractions were validated on large number of tre mutant embryos and NCX1h morphants (>500 embryos).
Zebrafish cardiac imaging

Videos of GFP-labelled myl7:GFP hearts were taken at 30 frames per second. Line-scan analysis was performed along a line through the atria or the ventricles of these hearts (Nguyen et al., 2009). Fraction of shortening was deduced from the ratio of diastolic and systolic width and heart rate was determined by beats per minute. Cardiac parameters were analyzed in tremblor<sup>Tc318</sup> and VDAC2<sup>LA2256</sup> at 2 dpf.

Zebrafish optical mapping

36 hpf myl7:gCaMP4.1 embryos were imaged at a frame rate of 30 ms/frame. Electromechanical isolation was achieved by tnt2MO (Milan et al., 2006). The fluorescence intensity of each pixel in a 2D map was normalized to generate heat maps and isochronal lines at 33 ms intervals were obtained by identifying the maximal spatial gradient for a given time point (Chi et al., 2008).

Mouse and human embryonic stem cells

The mouse E14Tg2a ESC and human H9 ESC line were cultured and differentiated as previously described (Blin et al., 2010; Arshi et al., 2013). At day 10 of differentiation, beating mouse EBs were exposed to external solution containing 10 mM CaCl<sub>2</sub> for 10 min before DMSO or efsevin (10 μM) treatment. Human EBs were differentiated for 15 days and treated with 5 mM CaCl<sub>2</sub> for 10 min before DMSO or efsevin (5 μM) treatment. Images of beating EBs were acquired at a rate of 30 frames/s and analyzed by motion-detection software. For calcium recording, the EBs were loaded with 10 μM fluo-4 AM in culture media for 30 min at 37°C. Line-scan analysis was performed and fluorescent signals were acquired by a Zeiss LSM510 confocal microscope.

Microelectrode array measurements

2-day-old wild type, tre, and efsevin-treated tre embryos were placed on uncoated, microelectrode arrays (MEAs) containing 120 integrated TiN electrodes (30 μm diameter, 200 μm interelectrode spacing). Local field potentials (LFPs) at each electrode were collected for three trials per embryo type over a period of three minutes at a sampling rate of 1 kHz using the MEA2100-HS120 system (Multichannel Systems, Reutlingen, Germany). Raw data was low-pass filtered at a cutoff frequency of 10 Hz using a third-order Butterworth filter. Data analysis was carried out using the MC_DataTool (Multichannel Systems) and Matlab (MathWorks).

Ca<sup>2+</sup> imaging

Murine ventricular cardiomyocytes were isolated as previously described (Reuter et al., 2004). Cells were loaded with 5 μM fluo-4 AM in external solution containing: 138.2 mM NaCl, 4.6 mM KCl, 1.2 mM MgCl<sub>2</sub>, 15 mM glucose, 20 mM HEPES for 1 hr and imaged in external solution supplemented with 2, 5 or 10 mM CaCl<sub>2</sub>. For the recording of Ca<sup>2+</sup> sparks and transients, the external solution contained 2 mM CaCl<sub>2</sub>. For Ca<sup>2+</sup> transients, cells were field stimulated at 0.5 Hz with a 5 ms pulse at a voltage of 20% above contraction threshold. For all measurements, efsevin was added 2 hr prior to the actual experiment. Images were recorded on a Zeiss LSM 5 Pascal confocal microscope. Data analysis was carried out using the Zeiss LSM Image Browser and ImageJ with the SparkMaster plugin (Picht et al., 2007). Cells were visually inspected prior to and after each recording. Only those recordings from
Figure 5. Efsevin enhances mitochondrial Ca\(^{2+}\) uptake. (A) HeLa cells were transfected with a flag-tagged zebrafish VDAC2 (VDAC2\(^{flag}\)), immunostained against the flag epitope and counterstained for mitochondria with MitoTracker Orange and for nuclei with DAPI. (B) Representative traces of mitochondrial matrix [Ca\(^{2+}\)]\(_{m}\) detected by

Figure 5. Continued on next page
healthy looking cells with distinct borders, uniform striations and no membrane blebs or granularity were included in the analysis.

Biochemistry

For pull down assays mono-N-Boc protected 2,2’-(ethylenedioxy)bis(ethylamine) was attached to the carboxylic ester of efsevin and its derivatives through the amide bond. After removal of the Boc group using TFA, the primary amine was coupled to the carboxylic acid of Affi-Gel 10 Gel (Biorad, Hercules, CA). 2-day-old zebrafish embryos were deyolked by centrifugation before being lysed with Rubinfeld’s lysis buffer (Rubinfeld et al., 1993). The lysate was precleaned by incubation with Affi-Gel 10 Gel to eliminate non-specific binding. Precleand lysate was incubated with affinity beads overnight. Proteins were eluted from the affinity beads and separated on SDS-PAGE. Protein bands of interest were excised. Gel plugs were dehydrated in ACN, and dried down in a Speedvac. Gel pieces were then swollen in digestion buffer containing 50 mM NH₄HCO₃ (30 min at 56°C) and 100 mM iodoacetamide (45 min in dark), respectively. Gel plugs were washed with 50 mM NH₄HCO₃, dehydrated with ACN, and dried down in a Speedvac. Gel pieces were extracted with 0.1% TFA in 50% ACN solution, dried down and resuspended in LC buffer A (0.1% formic acid, 2% ACN).

Mass spectrometry analyses and database searching

Extracted peptides were analyzed by nano-flow LC/MS/MS on a Thermo Orbitrap with dedicated Eksigent nanopump using a reversed phase column (New Objective, Woburn, MA). The flow rate was 200 nl/min for separation: mobile phase A contained 0.1% formic acid, 2% ACN in water, and mobile phase B contained 0.1% formic acid, 20% water in ACN. The gradient used for analyses was linear from 5% B to 50% B over 60 min, then to 95% B over 15 min, and finally keeping constant 95% B for 10 min. Spectra were acquired in data-dependent mode with dynamic exclusion where the instrument selects the top six most abundant ions in the parent spectra for fragmentation. Data were searched against the Danio rerio IPI database v3.45 using the SEQUEST algorithm in the BioWorks software program version 3.3.1 SP1. All spectra used for identification had deltaCN>0.1 and met the following Xcorr criteria: >2 (+1), >3 (+2), >4 (+3), and >5 (+4). Searches required full cleavage with the enzyme, ≤4 missed cleavages and were performed with the differential modifications of carboxylic acid and methionine oxidation.

In situ hybridization

In situ hybridization was performed as previously described (Chen and Fishman, 1996). DIG-labeled RNA probe was synthesized using the DIG RNA labeling kit (Roche, Indianapolis, IN).

Immunostaining

HeLa cells were transfected with a C-terminally flag-tagged zebrafish VDAC1 or VDAC2 in plasmid pCS2+ using Lipofectamine 2000 (Invitrogen). After staining with MitoTracker Orange (Invitrogen)
cells were fixed in 3.7% formaldehyde and permeabilized with acetone. Immunostaining was performed using primary antibody ANTI-FLAG M2 (Sigma Aldrich, St. Luis, MO) at 1:100 and secondary antibody Anti-Mouse IgG1-FITC (Southern Biotechnology Associates, Birmingham, AL) at 1:200. Cells were mounted and counterstained using Vectashield Hard Set with DAPI (Vector Laboratories, UK).

**Mitochondria Ca$^{2+}$ uptake assay in HeLa cells**

HeLa cells were transfected with zebrafish VDAC2 using Lipofectamine 2000 (Invitrogen, Carlsbad, CA). 36 hrs after transfection, cells were loaded with 5 µM Rhod2-AM (Invitrogen), a Ca$^{2+}$ indicator preferentially localized in mitochondria, for 1 hr at 15°C followed by a 30 min de-esterification period at 37°C. Subsequently, cells were permeabilized with 100 µM digitonin for 1 min at room temperature.

**Figure 6.** Effects of efsevin on isolated cardiomyocytes. (A) Electrically paced Ca$^{2+}$ transients at 0.5 Hz (top). Normalized quantification of Ca$^{2+}$ transient parameters reveals no difference for transient amplitude (efsevin-treated at 98.6 ± 4.5% of vehicle-treated) and time to peak (95 ± 3.9%), but a significant decrease for the rate of decay (82.8 ± 4% of vehicle- for efsevin-treated) (lower panel). (B) Representation of typical Ca$^{2+}$ sparks of vehicle- and efsevin treated cardiomyocytes (top). No differences were observed for spark frequency (101.1 ± 7.7% for efsevin-compared to vehicle-treated), maximum spark amplitude (101.6 ± 2.5%) and Ca$^{2+}$ release flux (98.7 ± 2.8%). In contrast, the decay phase of the single spark was significantly faster in efsevin treated cells (82.5 ± 2.1% of vehicle-treated). Consequently, total duration of the spark was reduced to 85.7 ± 2% and the total width was reduced to 89.5 ± 1.4% of vehicle-treated cells. *, p < 0.05; ***, p < 0.001. (C) Increasing concentrations of extracellular Ca$^{2+}$ induced a higher frequency of spontaneous propagating Ca$^{2+}$ waves in isolated adult murine ventricular cardiomyocytes. Efsevin treatment reduced Ca$^{2+}$ waves in a dose-dependent manner. (D) Quantitative analysis of spontaneous Ca$^{2+}$ waves spanning more than half of the entire cell. Addition of 1 µM efsevin reduced Ca$^{2+}$ waves to approximately half. Increasing the concentration of efsevin to 10 µM further reduced the number of spontaneous Ca$^{2+}$ waves and 25 µM efsevin almost entirely blocked the formation of Ca$^{2+}$ waves.

DOI: 10.7554/eLife.04801.026
Figure 7. Mitochondria regulate cardiac rhythmicity through a VDAC2-dependent mechanism. (A) MCU and MICU1 are expressed in the developing zebrafish hearts (arrowhead). (B) Overexpression of MCU is sufficient to restore coordinated cardiac contractions in tre embryos (47.1 ± 1.6% embryos, n = 112 as opposed to 18.3 ± 5.3% of uninjected siblings, n = 64) while this effect is significantly attenuated when co-injected with morpholino antisense oligonucleotide targeted to VDAC2 (27.1 ± 1.9% embryos, n = 135). (C) Suboptimal overexpression of MCU (MCU\textsuperscript{S}) and VDAC2 (VDAC2\textsuperscript{S}) in combination is able to suppress cardiac fibrillation in tre embryos (42.9 ± 2.6% embryos, n = 129). (D) The ability of VDAC2 to restore rhythmic contractions in tre embryos (48.5 ± 3.5% embryos, n = 111) is significantly attenuated when MCU is knocked down by antisense oligonucleotide (MO\textsubscript{MCU}) (25.6 ± 2.4% embryos, n = 115). (E) Overexpression of MICU1 is sufficient to restore rhythmic cardiac contractions in tre embryos (49.3 ± 3.4% embryos, n = 127 compared to 16.8 ± 1.4% of uninjected siblings, n = 150). This effect is abrogated by VDAC2 knockdown (MO\textsubscript{VDAC2}, 25.3 ± 5.5% embryos, n = 97). (F) Suboptimal overexpression of MICU1 (MICU1\textsuperscript{S}) and VDAC2 (VDAC2\textsuperscript{S}) in combination is able to restore rhythmic cardiac contractions in tre embryos (48.6 ± 6.0%, n = 106). Error bars represent s.d.; *p < 0.05; ***p < 0.001.

DOI: 10.7554/eLife.04801.027

The following figure supplement is available for figure 7:

Figure supplement 1. Expression of MCU, MICU1 and VDAC2.

DOI: 10.7554/eLife.04801.028

Fluorescence changes in Rhod2 (ex: 544 nm, em: 590 nm) immediately after the addition of Ca\textsuperscript{2+} (final free Ca\textsuperscript{2+} concentration is calculated to be approximately 10 µM using WEBMAXC at http://web.stanford.edu/~cpatton/webmaxc5.htm) were monitored in internal buffer (5 mM K-EGTA, 20 mM HEPES, 100 mM K-aspartate, 40 mM KCl, 1 mM MgCl\textsubscript{2}, 2 mM maleic acid, 2 mM glutamic acid, 5 mM pyruvic acid, 0.5 mM KH\textsubscript{2}PO\textsubscript{4}, 5 mM MgATP, pH adjusted to 7.2 with Trizma base) using a FLUOSTAR plate reader (BMG Labtech, Germany).

Mitochondria Ca\textsuperscript{2+} uptake assay in VDAC1/VDAC3 double knockout (V1/V3 DKO) MEFs

V1/V3 DKO MEFs were cultured as previously described (Roy et al., 2009a). Efsevin-treated (15 µM for 30 min) or mock-treated MEFs were used for measurements of [Ca\textsuperscript{2+}]\textsubscript{c} in suspensions of permeabilized cells or imaging of [Ca\textsuperscript{2+}]\textsubscript{m} simultaneously with [Ca\textsuperscript{2+}]\textsubscript{c} in intact single cells. Permeabilization of the
plasma membrane was performed by digitonin (40 μM/ml). Changes in [Ca^{2+}] in the cytoplasmic buffer upon IP_{3} (7.5 μM) addition in the presence or absence of ruthenium red (3 μM) was measured by fura2 in a fluorometer (Csordás et al., 2006; Roy et al., 2009b). To avoid endoplasmic reticulum Ca^{2+} uptake 2 μM thapsigargin was added before IP_{3}. For imaging of [Ca^{2+}]_{i} and [Ca^{2+}]_{c}, MEFs were co-transfected with plasmids encoding polycistronic zebrafish VDAC2 with mCherry and mitochondria-targeted inverse pericam for 40 hr. Cells were sorted to enrich the transfected cells and attached to glass coverslips. In the final 10 min, of the efsevin or mock-treatment, the cells were also loaded with fura2AM (2.5 μM) and subsequently transferred to the microscope stage. Stimulation with 1 μM ATP was carried out in a normally Ca^{2+} free buffer. Changes in [Ca^{2+}]_{i} and [Ca^{2+}]_{c}, were imaged using fura2 (ratio of ex:340 nm–380 nm) and mitochondria-targeted inverse pericam (ex: 495 nm), respectively (Csordas et al., 2010).

**Statistics**

All values are expressed as mean ± SEM, unless otherwise specified. Significance values are calculated by unpaired student’s t-test unless noted otherwise.

**Acknowledgements**

The authors thank Kenneth D Philipson, James N Weiss and Adam D Langenbacher for comments on the manuscript, Janice Ahn for assisting the initial chemical screen and Lingling Peng for the synthesis and Yi Chiao Fan for the characterization of efsevin and its derivatives. We also thank Jing Huang, James N Weiss and the UCLA cardiovascular research laboratory for reagents and infrastructure, and Jinghua Tang of UCLA-BSCRC for technical assistance on human ES cell works. We thank William Craigen for providing V1/V3 DKO MEFs.

**Additional information**

**Funding**

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<td>The Nakajima Foundation</td>
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<td>Graduate Student Fellowship</td>
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<td>Philip Whitcome Training Program, Graduate Student Fellowship</td>
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<td>Laubisch Foundation</td>
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<td>Austrian Science Fund</td>
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<td>Johann Schredelseker</td>
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<td>University of California, Los Angeles</td>
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The funders had no role in study design, data collection and interpretation, or the decision to submit the work for publication.

**Author contributions**

HS, Designed, performed, analyzed, and interpreted experiments, Wrote the manuscript, Conception and design, Acquisition of data, Analysis and interpretation of data, Drafting or revising the article;
effort was made to minimize suffering.

Animal Experiments (ARC# 2000-051-43B for the use of zebrafish) and Embryonic Stem Cell Research were approved by the Cedars-Sinai Institutional Animal Care and Use Committee (#003574 for the use of mouse cardiomyocytes), the Office of Animal Research Oversight that oversees the Ethics of Animal experimentation: This study was performed in strict accordance with the recommendations in the Guide for the Care and Use of Laboratory Animals of the National Institutes of Health. All of the animals were handled according to approved institutional animal care and use committee (IACUC) protocols of the University of California, Los Angeles and the Cedars-Sinai Hospital. The protocols were approved by the Cedars-Sinai Institutional Animal Care and Use Committee (#003574 for the use of mouse cardiomyocytes), the Office of Animal Research Oversight that oversees the Ethics of Animal Experiments (ARCE 2000-051-43B for the use of zebrafish) and Embryonic Stem Cell Research Oversight (#2009-006-06 for the use of ES cells) of the University of California, Los Angeles. Every effort was made to minimize suffering.

References


