Mechanisms of Sudden Cardiac Death
Oxidants and Metabolism
Kai-Chien Yang, John W. Kyle, Jonathan C. Makielski, Samuel C. Dudley Jr

Abstract: Ventricular arrhythmia is the leading cause of sudden cardiac death (SCD). Deranged cardiac metabolism and abnormal redox state during cardiac diseases foment arrhythmogenic substrates through direct or indirect modulation of cardiac ion channel/transporter function. This review presents current evidence on the mechanisms linking metabolic derangement and excessive oxidative stress to ion channel/transporter dysfunction that predisposes to ventricular arrhythmias and SCD. Because conventional antiarrhythmic agents aiming at ion channels have proven challenging to use, targeting arrhythmogenic metabolic changes and redox imbalance may provide novel therapeutics to treat or prevent life-threatening arrhythmias and SCD. (Circ Res. 2015;116:1937-1955. DOI: 10.1161/CIRCRESAHA.116.304691.)

Key Words: cardiac arrhythmias ■ death, sudden, cardiac ■ metabolism ■ oxidative stress

Sudden cardiac death (SCD) refers to death after an unexpected sudden cardiac arrest in a patient with or without known structural heart disease. The incidence of SCD in the United States ranges from 300,000 to 460,000 events per year, depending on the criteria for SCD used for surveillance. SCD results from a complex interaction between preexisting cardiac substrates, either structural or genetic, with superimposed physiological or environmental triggers. The most common underlying causal disorders for SCD in adults aged ≥35 are coronary heart disease (65%–80%) and dilated cardiomyopathy (10%–15%). Various types of cardiomyopathy (eg, hypertrophic cardiomyopathy, arrhythmogenic right ventricular cardiomyopathy, infiltrative, inflammatory, and valvular diseases), genetically determined rhythm disorders (eg, long-QT syndrome, Brugada syndrome, and catecholaminergic polymorphic ventricular tachycardia), or developmental disorders (anomalous origins of coronary arteries) account for most of the remaining SCDs. The epidemiology...
SCD.5,6 In general, ventricular tachyarrhythmias, including SCD, vary with the patient population and the criteria used to define the presence of an anatomic or functional disturbance of cardiac electric impulse propagation and of heterogeneous conduct. Abnormal automaticity results from the accelerated propagation of an action potential by a region of ventricular cells. Triggered activity occurs when an action potential elicits subsequent depolarizations earlier (early afterdepolarization [EAD]) or later (delayed afterdepolarization [DAD]) in the repolarization phase.

All 3 mechanisms can result from abnormal functioning of myocardial ion channels and transporters, leading to disordered initiation or propagation of cardiac action potentials. Accumulating evidence suggests that altered cardiac ion channel/transporter function is closely linked to abnormal myocardial metabolic activity and increased oxidative stress on myocardial ion channel/transporters that predispose to ventricular arrhythmias and SCD. It is important, however, to recognize that abnormal metabolism and oxidative stress in noncardiac myocytes tissues can also contribute to the development of ventricular arrhythmias. For example, altered metabolism and redox state have been implicated in vascular tissue leading to atherosclerosis, which underlies the main substrate for SCD and coronary heart disease.2,3 Another example is that abnormal metabolism and increased oxidative stress affect autonomic nervous system, thereby contributing to ventricular arrhythmias and SCD.4-7 Within the ventricle, chronic effects of such entities as diabetes mellitus and ischemia from atherosclerosis work through mechanisms involving metabolic and oxidative abnormalities to create the substrate of structural heart diseases that leads to SCD. Both the role of aberrant metabolism and oxidants in the chronic creation of such substrate will not be further considered.

Overview of Cardiac Ionic Channels and Membrane Excitability

Normal functioning of the mammalian heart depends on proper electric activity involving the initiation of the electric impulse from pacemaker cells, the propagation of the electric activity through specialized conduction system and myocardium, and the generation of action potentials in individual myocytes.8,9 A normal cardiac cycle begins with the action potential originating from the cells in sinoatrial node, conducts through the atria, atrioventricular node, His bundle, Purkinje fibers, and then spreads throughout the entire ventricular myocardium.10 The proper propagation of cardiac electric impulse depends on low resistance pathways between cells via gap junctions, which are formed by docking of 2 connexin hemichannels on appositional sarcolemmal membranes.11

Cardiac action potentials are generated through the coordinated activity of various types of ion channels and transporters (Figure 1). Inward current conducting through the voltage-gated Na+ channel rapidly depolarizes the cell (phase 0), which is followed by early repolarization (phase 1) attributed to the transient outward K+ current (Ito). Depolarizing L-type Ca2+ currents (ICa,L) and multiple repolarizing delayed rectifier K+ currents (IK) form the plateau phase (phase 2), which is followed by rapid repolarization (phase 3) with inactivated Ica,l and increasing IK. The repolarization continues with the contribution of inwardly rectifying K+ current, IK, until return to the resting membrane potential (phase 4). The Ca2+ influx during the

<table>
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<th>Nonstandard Abbreviations and Acronyms</th>
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<tr>
<td>ΔVm</td>
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<td>AMPK</td>
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and causes of SCD have been extensively reviewed previously and in the articles on epidemiology of sudden cardiac death in this compendium series.

The physiological mechanisms reported to cause SCD vary with the patient population and the criteria used to define SCD.5,6 In general, ventricular tachyarrhythmias, including ventricular fibrillation and pulseless ventricular tachycardia, are the most common electrophysiological mechanisms leading to SCD.5,7 Other physiological events that can result in SCD include pulseless electric activity, bradyarrhythmias, and asystole.8,9 This review will focus only on SCDS attributed to ventricular tachyarrhythmias.

Ventricular tachyarrhythmias, like all cardiac arrhythmias, result from 1 of 3 primary mechanisms: reentry, abnormal automaticity, or triggered activity. Reentry is the most common mechanism for ventricular tachyarrhythmias, involving the presence of an anatomic or functional disturbance of cardiac electric impulse propagation and of heterogeneous conduction. Abnormal automaticity results from the accelerated generation of an action potential by a region of ventricular cells. Triggered activity occurs when an action potential elicits
Extruding 1 Ca\textsuperscript{2+} ion from the myocyte in exchange for three chemical Na\textsuperscript{+} gradient and K\textsuperscript{+} gradient provides the driving force for many other transporter/exchangers. Conditions that impair the activity of the aforementioned ion channels/transporters can result in abnormal myocardial electric functioning, leading to ventricular arrhythmias and SCD.

**Myocardial Metabolism and Energetics**

Under physiological conditions, >90% of ATP produced in the cardiac myocytes is supplied by mitochondria via oxidative phosphorylation (OXPHOS), and the remainder comes from glycolysis and GTP derived from the tricarboxylic acid cycle.\textsuperscript{22} As the predominant energy generator in the heart, mitochondria occupy \approx30\% of the volume of cardiac myocytes.\textsuperscript{23} The mitochondria have double-membrane structure (inner and outer membranes) that forms separate compartments, the intermembrane space, and mitochondrial matrix. Mitochondria metabolize predominantly fatty acids but can metabolize glucose to generate ATP via OXPHOS. Acetyl-CoA, the metabolic intermediate derived from sequential oxidation of glucose and fatty acid, is used to generate the reducing equivalents, nicotinamide adenine dinucleotide (NADH), and flavin adenine dinucleotide (FADH\textsubscript{2}), in the tricarboxylic acid cycle. NADH and FADH\textsubscript{2} feed electrons to the electron-transport chain (ETC) residing on the mitochondrial inner membrane (Figure 2), where the electrons pass sequentially through complex I, II, III, and IV and finally interact with molecular O\textsubscript{2} to form H\textsubscript{2}O. Redox reactions occur at complex I, III, and IV, driving proton (H\textsuperscript{+}) from mitochondrial matrix into the intermembrane space. The resulting proton gradient and strongly negative mitochondrial membrane potential ($\Delta\Psi_m$=-150 to -180 mV)\textsuperscript{24} help to drive H\textsuperscript{+} flow back to the matrix through mitochondrial ATP synthase (complex V), allowing the conversion of ADP to ATP (Figure 2).

In healthy adult myocardium, 60\% to 90\% of acetyl-CoA comes from $\beta$-oxidation of fatty acids, whereas 10\% to 40\% comes from oxidation of pyruvate derived from glycolysis and lactate oxidation.\textsuperscript{25,26} Although the majority of cardiac ATP is consumed by the myofilaments, it is estimated that \approx25\% of cardiac ATP hydrolysis is used to fuel sarcocellular and SR ion channels and transporters.\textsuperscript{27} The critical dependence of cardiac ion channels and transporters on energy supply from metabolized carbon fuels becomes evident under conditions such as myocardial ischemia, during which the mismatch between ATP supply and use can readily disrupt the cardiac rhythm through depleting energy supply to these channels and transporters.\textsuperscript{28,29}

**Cardiac Oxidants and Oxidative Stress**

In biological systems, partially reduced forms of oxygen (O\textsubscript{2}) lead to the formation of oxidants or reactive oxygen species (ROS), which oxidize other molecules when these molecules accept electrons. The main ROS in cardiac myocytes exist in radical forms, such as superoxide (O\textsubscript{2}^-) and hydroxyl radicals, or in nonradical forms, such as hydrogen peroxide (H\textsubscript{2}O\textsubscript{2}), hypochlorite, nitric oxide (NO), and peroxynitrite. It is important to note that although grouped under the acronym of ROS, different reactive species containing molecular oxygen vary greatly in diffusion coefficient, reactivity, and oxidation potential.
Under physiological conditions, trace amounts of signaling ROS, which are tightly regulated by the balance of ROS production and ROS scavengers, form a network that coordinates metabolism with gene transcription and enzymatic activity. Low levels of ROS produced during short periods of ischemia, for example, trigger signaling pathways that confer cardiac protection, a phenomenon coined ischemic preconditioning (IPC), which is mediated, at least in part, through mitochondrial KATP channels (see below). In addition, low levels of nicotinamide adenine dinucleotide phosphate (NADPH) oxidase 2–mediated ROS production sensitizes nearby RyRs and triggers Ca2+ sparks in cardiac myocytes in response to physiological stretch with increased preload and afterload, a process termed X-ROS signaling. Excessive ROS leads to detrimental reactions with cellular lipids and proteins, eliciting maladaptive responses and other abnormalities that compromise cellular and tissue functions, ultimately leading to cell death. The deleterious effects caused by excessive ROS are defined as oxidative stress.

The main sources of ROS in cardiac myocytes include NADPH oxidases, xanthine oxidase, nitric oxide synthase (NOS), and mitochondria. Figure 3 illustrates the major ROS synthesis pathways in cardiac myocytes. NADPH oxidases are membrane-bound enzymes that use NADH or NADPH as the electron donor to generate O2•− from O2. Xanthine oxidase catalyzes the oxidation of hypoxanthine/xanthine and produces O2•−. NOS, on the contrary, produces a single nitrogen radical (NO•) through metabolizing L-arginine to L-citrulline. NOS becomes uncoupled under conditions such as depletion of L-arginine, oxidation of the NOS cofactor tetrahydrobiopterin, or increased S-glutathionylation of NOS. Under these conditions, NOS produces O2•− instead of NO•. NO• itself is a weak thiol oxidant, but it regulates various physiological functions by activating cGMP/protein kinase G (PKG) pathways or by covalent modification of protein cysteine residues via S-nitrosylation or S-glutathiolation (GSS-); NO• also reacts with O2•− and forms a more potent oxidative molecule peroxynitrite. Oxidative molecules derived from NO•, such as NO2•, N2O3, and peroxynitrite, are termed reactive nitrogen species. As the metabolic hub in cardiac myocytes, mitochondria consume most of the O2 in cardiac myocytes for energy production, thereby serving as the major source of ROS in the heart.
leading to $O_{2}^{-}$ formation (Figure 2).46 The ROS production rate in the mitochondria is accelerated by increased proton motive force, by the increased NADH/NAD$^{+}$ ratio, by the increased ratio of reduced coenzyme Q10 to coenzyme Q10, or when the O$_{2}$ concentration is raised above physiological levels.47,48 Paradoxically, mitochondrial ROS production also increases under condition of low local O$_{2}$ concentration.47,49 Mitochondrial O$_{2}^{-}$ is converted to H$_{2}$O$_{2}$ and O$_{2}$ by manganese superoxide dismutase, the primary antioxidant enzyme in mitochondria.50 H$_{2}$O$_{2}$ is then converted to H$_{2}$O and O$_{2}$ by manganese superoxide dismutase, the primary antioxidant enzyme in mitochondria.50 H$_{2}$O$_{2}$ is then converted to H$_{2}$O and O$_{2}$ by manganese superoxide dismutase, the primary antioxidant enzyme in mitochondria.50 H$_{2}$O$_{2}$ is then converted to H$_{2}$O and O$_{2}$ by manganese superoxide dismutase, the primary antioxidant enzyme in mitochondria.50 H$_{2}$O$_{2}$ is then converted to H$_{2}$O and O$_{2}$ by manganese superoxide dismutase, the primary antioxidant enzyme in mitochondria.50 H$_{2}$O$_{2}$ is then converted to H$_{2}$O and O$_{2}$ by manganese superoxide dismutase, the primary antioxidant enzyme in mitochondria.50 H$_{2}$O$_{2}$ is then converted to H$_{2}$O and O$_{2}$ by manganese superoxide dismutase, the primary antioxidant enzyme in mitochondria.50 H$_{2}$O$_{2}$ is then converted to H$_{2}$O and O$_{2}$ by manganese superoxide dismutase, the primary antioxidant enzyme in mitochondria.50 H$_{2}$O$_{2}$ is then converted to H$_{2}$O and O$_{2}$ by manganese superoxide dismutase, the primary antioxidant enzyme in mitochondria.50 H$_{2}$O$_{2}$ is then converted to H$_{2}$O and O$_{2}$ by manganese superoxide dismutase, the primary antioxidant enzyme in mitochondria.50 H$_{2}$O$_{2}$ is then converted to H$_{2}$O and O$_{2}$ by manganese superoxide dismutase, the primary antioxidant enzyme in mitochondria.50 H$_{2}$O$_{2}$ is then converted to H$_{2}$O and O$_{2}$ by manganese superoxide dismutase, the primary antioxidant enzyme in mitochondria.50

The mitochondrial ETC efficiency is impaired under pathological conditions, such as myocardial ischemia and heart failure, resulting in increased electron leak and ROS production. Accumulating ROS levels trigger the opening of mitochondrial permeability transition pore (PTP) and inner membrane anion channel (IMAC) (Figure 2), leading to depolarization of the ΔΨ$_{m}$ and further acceleration of ROS production, a phenomenon termed mitochondrial ROS-induced ROS release.60,62 The PTP is a nonselective channel residing on the inner mitochondrial membrane, and it opens with elevated matrix [Ca$^{2+}$], increased ROS and phosphate levels, and by reduced...
great escape mechanism, producing spontaneous waves of Ca²⁺ release,96 which can lead to calcium transient/action potential alternans.95,97 On reperfusion or reoxygenation, RyR2 is released from inhibition,98,99 but reactivation seems to predominate over reduced SERCA activity28; however, RyR2 inhibition seems to predominate over reduced SERCA activity during ischemia,100 leading to increased intracellular Na⁺ accumulation.101,102 The capacity of Ca²⁺ uptake and release by SERCA also contributes to increased intracellular Ca²⁺ levels during myocardial ischemia.101 Elevated intracellular Ca²⁺ leads to increased cytosolic Ca²⁺, which at least in part, through decreased extrusion of Ca²⁺ or through actual Ca²⁺ entry with NCX activity in the reverse mode (Na⁺ out and Ca²⁺ in).92–94 The activity of SR Ca²⁺ uptake (through SERCA) and release (through RyR2) are both inhibited during myocardial ischemia;28 however, RyR2 inhibition seems to predominate over reduced SERCA activity during ischemia, reflected in lower frequency of spontaneous Ca²⁺ release through RyR228,95 and increased SR Ca²⁺ load.28 On reperfusion or reoxygenation, RyR2 is released from inhibition, producing spontaneous waves of Ca²⁺ release,28 which may contribute to calcium transient/action potential alternans and increase the risk of ventricular arrhythmias (Figure 4; Table 1).97,98

In addition to the ATP production machinery, mitochondria also harbor Ca²⁺ channels and transporters, allowing the transfer of Ca²⁺ ions between cytosol and mitochondria, thereby contributing to the dynamic regulation of sarcomeral Ca²⁺ homeostasis. Mitochondria uptake Ca²⁺ predominantly through the mitochondrial Ca²⁺ uniporter and extrude Ca²⁺ mainly through the mitochondrial Na⁺:Ca²⁺ exchanger (Figure 2).99,100 The capacity of Ca²⁺ uptake and release by mitochondria forms an additional buffer for cytosolic Ca²⁺ regulation, contributing to the spatiotemporal dynamics of Ca²⁺ signaling in cardiac cells.101,102 Nevertheless, it remains debatable how much mitochondria contribute to cellular Ca²⁺.
dynamics under physiological and pathological conditions.\textsuperscript{103} Recently, Williams et al\textsuperscript{102} provide quantitative data, suggesting that mitochondria do not function as a significant buffer of cytosolic Ca\textsuperscript{2+} under physiological conditions, with prolonged elevation of cytosolic [Ca\textsuperscript{2+}]; however, mitochondrial Ca\textsuperscript{2+} uptake can increase \texttimes{}1000-fold and affect cellular Ca\textsuperscript{2+} dynamics significantly.\textsuperscript{102} Nevertheless, it has been shown that mitochondrial dysfunction results in cardiac myocytes Ca\textsuperscript{2+} transient alternans by impairing the mitochondrial capacity of Ca\textsuperscript{2+} handling, thereby predisposing to cardiac arrhythmias.\textsuperscript{104} In addition, pharmacological inhibition of mitochondrial uptake through mitochondrial Ca\textsuperscript{2+} uniporter with Ru360 has been shown to reduce the incidence of ventricular arrhythmias induced by ischemia-reperfusion in the rodent heart.\textsuperscript{105} As the metabolic center in cardiac myocytes, therefore, mitochondria play an important role in transducing changes in cardiac metabolic states to the dynamic regulation of sarcolemmal Ca\textsuperscript{2+}, membrane excitability, and electric functioning.

### Metabolic Regulation of Na\textsuperscript{+} Homeostasis and Na\textsuperscript{+} Channel Function

Intracellular [Na\textsuperscript{+}] plays a critical role in regulating the energetics, electric functioning, and contractility of cardiac myocytes, which can be attributed to the direct and indirect effects of cytosolic [Na\textsuperscript{+}] on Ca\textsuperscript{2+} homeostasis,\textsuperscript{92} mitochondrial function,\textsuperscript{106} and cellular signaling.\textsuperscript{107} Multiple ion channels/transporters function to maintain the [Na\textsuperscript{+}] homeostasis in cardiac myocytes: Na\textsuperscript{+}/K\textsuperscript{+} ATPase, for example, consumes ATP to pump Na\textsuperscript{+} outside of the cell in exchange of K\textsuperscript{+}, representing the main mechanism of Na\textsuperscript{+} efflux, whereas Na\textsuperscript{+} channels, NCX, and the Na\textsuperscript{+}/H\textsuperscript{+} exchanger (NHE) mediate Na\textsuperscript{+} influx in cardiac myocytes.

Cardiac voltage-gated Na\textsuperscript{+} channels form by the assembly of a pore-forming α subunit and auxiliary β subunits that modulate channel activities. Nav1.5 (SCN5A) is the predominant Nav α subunit expressed in the mammalian cardiac myocytess. During ischemia/metabolic inhibition, connexin hemichannels at the intercalated discs between cardiac myocytes are nonselective cation channels that are permeable to Na\textsuperscript{+}, K\textsuperscript{+}, and Ca\textsuperscript{2+}.\textsuperscript{112,114} With the high conductance of these connexin hemichannels, it is suggested that the opening of even a small number of connexin 43 hemichannels can lead to doubling of Na\textsuperscript{+} influx in ventricular cardiac myocytes,\textsuperscript{112,114} contributing to increased Na\textsuperscript{+} load and increased propensity for arrhythmias (Table 1; Figure 4).

During the metabolic stress that ensues with myocardial ischemia/reperfusion, reduced Na\textsuperscript{+}/K\textsuperscript{+} ATPase (because of reduced ATP and elevated ADP/phosphate levels), increased late I\textsubscript{Na} (see below for detailed mechanisms),\textsuperscript{108} and enhanced NHE (owing to increased cytosolic acidosis) activity\textsuperscript{109,110} result in increased cytosolic [Na\textsuperscript{+}], thereby leading to Ca\textsuperscript{2+} overload and increased propensity for ventricular arrhythmias (see above). It has been shown that pharmacological inhibition or knockout of NHE renders cardiac function resistant to ischemia-reperfusion injury.\textsuperscript{111}

In addition to altered Na\textsuperscript{+}/K\textsuperscript{+} ATPase and NHE function, it has been demonstrated that ischemia/metabolic inhibition can trigger Na\textsuperscript{+} influx through connexin hemichannels.\textsuperscript{112,113} Under normal conditions, connexin hemichannels located on adjacent intercellular sarcolemmal membranes combine to form gap junctions at the intercalated discs between cardiac myocytes. During ischemia/metabolic inhibition, connexin hemichannels localize to the nonfunctional membrane, turning into nonselective cation channels that are permeable to Na\textsuperscript{+}, K\textsuperscript{+}, and Ca\textsuperscript{2+}.\textsuperscript{112,114} With the high conductance of these connexin hemichannels, it is suggested that the opening of even a small number of connexin 43 hemichannels can lead to doubling of Na\textsuperscript{+} influx in ventricular cardiac myocytes, contributing to increased Na\textsuperscript{+} load and increased propensity for arrhythmias (Table 1; Figure 4).

Elevated cytosolic [Na\textsuperscript{+}] also impairs cardiac metabolism reciprocally through affecting mitochondrial function. Mitochondrial [Na\textsuperscript{+}] is regulated by NHE-mediated Na\textsuperscript{+} uptake\textsuperscript{116} and mitochondrial Na\textsuperscript{+}/Ca\textsuperscript{2+} exchanger–mediated Na\textsuperscript{+} efflux.\textsuperscript{117} Under physiological conditions, energized mitochondria extrude H\textsuperscript{+}, and the resulting pH gradient drives the Na\textsuperscript{+} gradient between mitochondrial matrix (lower [Na\textsuperscript{+}]) and cytosol (higher [Na\textsuperscript{+}]).\textsuperscript{116,118} Intracellular Na\textsuperscript{+} levels increase significantly in pathological conditions, such as myocardial

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**Table 1. Effects of Metabolic Changes on Cardiac Ion Channel/Transporter Function and Arrhythmogenicity**

<table>
<thead>
<tr>
<th>Channel/Transporter Effects</th>
<th>Metabolic Changes</th>
<th>Effects on Electric/Ionic Homeostasis</th>
<th>Proarrhythmic Mechanism</th>
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<tbody>
<tr>
<td>Na\textsuperscript{+}/K\textsuperscript{+} ATPase ↓</td>
<td>Ischemia/hypoxia</td>
<td>Na\textsuperscript{+} overload</td>
<td>Ca\textsuperscript{2+} overload and DAD</td>
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<tr>
<td>Cx hemichannel ↑</td>
<td>Ischemia</td>
<td>Na\textsuperscript{+} overload</td>
<td>Ca\textsuperscript{2+} overload and DAD</td>
</tr>
<tr>
<td>Peak I\textsubscript{Na} ↓</td>
<td>Ischemia/heart failure</td>
<td>↓ Na\textsuperscript{+} influx</td>
<td>Slow conduction</td>
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<tr>
<td>Late I\textsubscript{Na} ↑</td>
<td>Ischemia/hypoxia</td>
<td>↑ Na\textsuperscript{+} influx, prolonged APD</td>
<td>EAD</td>
</tr>
<tr>
<td>Kv ↓</td>
<td>Diabetes mellitus, heart failure</td>
<td>↓ K\textsuperscript{+} influx, prolonged APD</td>
<td>EAD</td>
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<tr>
<td>Kv↑</td>
<td>Insulin treatment in diabetic heart, PI3Kα activation, exercise training</td>
<td>↑ K\textsuperscript{+} channel expression</td>
<td>Protective</td>
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<tr>
<td>I\textsubscript{KATP} ↑</td>
<td>Ischemia</td>
<td>↑ K\textsuperscript{+} influx, shortened APD</td>
<td>Current sink, slow conduction</td>
</tr>
<tr>
<td>RyR2 ↓</td>
<td>during ischemia, ↑ on reperfusion</td>
<td>SR Ca\textsuperscript{2+} load ↑, spontaneous Ca\textsuperscript{2+} waves ↑</td>
<td>Ca\textsuperscript{2+} transient/action potential alternans</td>
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</tbody>
</table>

APD, action potential duration; Cx, connexin; DAD, delayed afterdepolarization; EAD, early afterdepolarization; I\textsubscript{Na}, ATP-sensitive K\textsuperscript{+} current; Kv, voltage-gated K\textsuperscript{+} current; Late I\textsubscript{Na}, late Na\textsuperscript{+} current; LPC, lysophosphatidylcholine; Peak I\textsubscript{Na}, peak Na\textsuperscript{+} current; RyR2, ryanodine receptor 2; and SR, sarcoplasmic reticulum.

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The dynamic regulation of sarcolemmal Ca\textsuperscript{2+}, membrane excitability, and electric functioning.
ischemia. The rise in cytosolic [Na+] during ischemia widens the Na+ gradient across mitochondria, leading to stronger driving force for Ca2+ extrusion from mitochondria via mitochondrial Na+-Ca2+ exchanger, thereby leading to reduced mitochondrial [Ca2+] and altered mitochondrial energetics, including decreased activities of Ca2+-dependent dehydrogenases in the tricarboxylic acid cycle, the net oxidation of the matrix NADH/NADPH pool, and hence the deficiency of NADPH-dependent ROS scavengers, thereby increasing mitochondrial ROS emission. Increased ROS levels further aggravate cytosolic Na+ accumulation by increasing late I\textsubscript{Na}, through direct Na+ channel modification or by activating signaling molecules such as PKC or CaMKII (see below). Therefore, there may be a feed-forward mechanism between increased cytosolic [Na+], impaired mitochondrial metabolism, increased ROS emission, and ROS-induced elevation of cytosolic [Na+].

In addition to cytosolic [Na+], cardiac metabolism also influences electric functioning through modulating sarcolemmal Na+ channel activity. During myocardial ischemia, various metabolic derangements result in altered Na+ channel properties and function. The ischemic metabolite lysophosphatidylcholine, for example, has been shown to decrease peak Na+ current (peak I\textsubscript{Na}) and to slow its inactivation. In addition, lysophosphatidylcholine also causes a marked increase in late I\textsubscript{Na}, thereby increasing myocardial Na+ loading. Myocardial acidosis during ischemia is also known to affect the inactivation states of Na+ channel, leading to increased late I\textsubscript{Na} (Table 1; Figure 4). Cardiac Na+ channels are reported to be modulated by AMP-activated PK (AMPK). AMPK is a serine/threonine kinase that is activated by increased cytosolic AMP/ATP ratio to increase ATP production and decrease ATP consumption, thereby functioning as a master metabolic regulator in cardiac myocytes. Mutations in PRKAG2 gene, which encodes the \gamma\textsubscript{2} subunit of AMPK, have been reported to be associated with electric instability and lethal ventricular arrhythmias. For example, PRKAG2 T172D, a constitutively active AMPK mutant, has been shown to slow Na+ channels inactivation, leading to increased late I\textsubscript{Na}, prolonged APD and arrhythmogenic EADs.

Metabolic Regulation of K+ Channels and Cardiac Repolarization

Various types of voltage-gated K+ (Kv) channels and nonvoltage-gated inwardly rectifying channels contribute to myocardial action potential repolarization. Under pathological conditions, such as myocardial ischemia, diabetes mellitus, and heart failure, repolarizing Kv currents in ventricular cardiac myocytes are reduced, leading to delayed repolarization and prolonged APD, which predispose to the development of ventricular arrhythmias and SCD (Figure 4). Among several types of inwardly rectifying K+ channels functioning in mammalian heart, I\textsubscript{K1} contributes to the terminal phase of repolarization and the maintenance of resting membrane potentials in ventricular myocytes, whereas currents conducted via sarclemmal K\textsubscript{ATP} (sarcK\textsubscript{ATP}) channels, gated by intracellular ATP/ADP levels and acidosis, function as immediate sensors of cellular metabolism and play an essential role in electrophysiological responses to metabolic stresses such as myocardial ischemia.

Abnormal cardiac repolarization, including QT-interval prolongation and T-wave abnormalities, are often observed in patients with diabetes mellitus, one of the leading chronic metabolic disorders associated with ventricular arrhythmias and SCD. Studies on cellular mechanisms of diabetes mellitus–induced repolarization abnormalities have consistently revealed downregulation of cardiac Kv currents in diabetic heart. Multiple mechanisms have been proposed to account for reduced Kv currents during diabetes mellitus. First, post-translational inhibition of Kv channel function occurs in diabetes mellitus. Plasma levels of free fatty acid metabolites, such as palmitoylcarnitine and palmitoyl-CoA, are increased with diabetes mellitus. They have been shown to inhibit cardiac Kv currents directly. Acute treatment with insulin has been demonstrated to reverse diabetes mellitus–induced Kv current reduction, suggesting the primary role of insulin-dependent signaling on Kv channel function. It has been suggested that improved glucose utilization by insulin may be responsible for restored Kv current expression because compounds known to improve glucose utilization (such as dichloroacetate or l-carnitine) have been shown to normalize cardiac Kv current density with diabetes mellitus. Increased ROS levels also contribute to reduced cardiac Kv currents during diabetes mellitus, and direct incubation with antioxidant glutathione has been shown to restore Kv current expression in myocytes isolated from diabetic hearts. Second, transcriptional regulation of Kv channel expression may reduce Kv currents. Peroxisome proliferator-activated receptor \alpha, a critical regulator of glucose/fatty acid metabolism, is upregulated in diabetic heart and has been suggested to transcriptionally repress cardiac Kv channel expression. Cardiac-specific overexpression of peroxisome proliferator-activated receptor \alpha downregulates the mRNA and protein expression levels of Kv4.2 and KChIP2, the channel subunits encoding I\textsubscript{to}, whereas peroxisome proliferator-activated receptor \alpha knockout upregulates I\textsubscript{to}. Interestingly, it has been recently demonstrated that the activation of phosphoinositide 3-kinase \alpha, a key component of insulin receptor signaling pathway that can be triggered by insulin treatment or exercise training, upregulates mRNA levels of various Kv channels through an Akt-independent mechanism, which may provide the mechanistic explanation for insulin-mediated Kv current modulation, as well as the metabolic impact of exercise training on cardiac repolarization. It is important to note that the changes in Kv current observed with diabetes mellitus or exercise training reflect the chronic effects of metabolic stress on Kv channel remodeling, rather than acute channel effects.

The sarcK\textsubscript{ATP} channels are present at high density in the sarclemmal membrane. SarcK\textsubscript{ATP} channels are inhibited by ATP and activated by ADP, Mg\textsuperscript{2+}, or low pH, conditions that are associated with ischemia, insufficient fuel supply, and increased metabolic stress. On increased metabolic stress with ATP depletion and acidosis (eg, during myocardial ischemia), sarcK\textsubscript{ATP} channels are activated, allowing an inwardly rectifying repolarizing K+ current. SarcK\textsubscript{ATP} channels open...
within seconds in response to acute ischemia, which is likely attributed to the rapid drop in pH (also within seconds of ischemia) in the ischemic tissue. ATP levels, by contrast, deplete at a slower rate and remain in the millimolar range (levels that are sufficient to keep sarcKATP channels closed) until 10 to 15 minutes after the onset of ischemia. Therefore, ATP depletion may not contribute to sarcKATP channel opening during the early phase of ischemia.

The cell surface expression density of sarcKATP channels is high. It has been estimated that the opening of merely 1% of the sarcKATP channels is sufficient to significantly shorten myocardial APD. The opening of sarcKATP channels shortens APD and decreases inward Ca2+ currents, thereby reducing Ca2+-mediated cardiac energy consumption and preventing Ca2+ overload-induced cell death. With adequate numbers of sarcKATP channels in the open state, however, cardiac myocytes become hyperpolarized and rendered extinguishable. This creates a current sink that slows or blocks electric propagation in the myocardium, predisposing to the development of arrhythmogenesis in the myocardium, predisposing to the development of ventricular arrhythmia. Interestingly, it has been shown that ATP production with impaired respiratory chain function leads to a decrease in ventricular arrhythmias in animal models and in humans. Reduced mitochondrial ATP production with impaired respiratory chain function leads to the activation of sarcKATP channels. During ROS-induced ROS release, for example, dissipation of ΔΨm results in cessation of mitochondrial ATP production, leading to sarcKATP activation, altered myocyte APDs and even ventricular arrhythmias. Interestingly, it has been shown that ATP generated from glycolysis plays a major role in modulating sarcKATP activity than ATP generated from OXPHOS, which is in accordance with recent findings that the key glycolytic enzymes, including glyceraldehyde 3-phosphate dehydrogenase (GAPDH) and pyruvate kinase, serve as components of the sarcKATP channel macrocomplex and regulate its function. SarcKATP channels have also been shown to exhibit reduced sensitivity to ATP-mediated inhibition in diabetic heart, resulting in higher sarcKATP conductance and greater APD shortening in response to hypoxia.

Non–Ion Channel Mechanisms Linking Metabolism to Ventricular Arrhythmias and SCD

As mentioned above, AMPK functions as a key metabolic sensor and regulator in cardiac myocytes. It has been reported that specific mutations in PRKAG2, the γ2 regulatory subunit of AMPK, lead to a glycogen storage cardiomyopathy characterized by ventricular pre-excitation and cardiac hypertrophy. The structural abnormalities associated with PRKAG2 mutations, including the glycogen accumulation and ventricular hypertrophy, result in abnormal conduction that predisposes to ventricular arrhythmias. In addition to AMPK, patients with inherited fatty acid oxidation disorders exhibit high incidence of ventricular arrhythmias, conduction defects and SCD, which can be attributed to the accumulation of arrhythmogenic intermediary metabolites of fatty acids. Fatty acid metabolites, such as lysocephosphatidylcholine, accumulate during myocardial ischemia, contributing to the formation of arrhythmogenic substrates. Consistent with these findings, a transgenic mouse model of cardiac-specific overexpression of fatty acid transport protein 1 (α-MHC FATP1) has been shown to exhibit increased myocardial uptake and accumulation of free fatty acids, leading to arrhythmogenic electric changes including QT prolongation. Taken together, these data suggest that abnormal cardiac metabolism can lead to ventricular arrhythmias and SCD through non–ion channel mechanisms.

Mechanisms Linking Increased Cardiac Oxidative Stress to Ventricular Arrhythmias and SCD

Myocardial Oxidative Stress and Cardiac Na+ Channels

Abnormal cardiac Na+ channel function is often observed in cardiac diseases, such as myocardial ischemia and heart failure, conditions that are associated with increased cardiac oxidative stress. Na+ channel abnormalities can be categorized as loss- or gain-of function. Loss-of-function Na+ channel abnormality leads to reduced peak INa, resulting in conduction block that potentiates re-entrant type ventricular arrhythmias. Gain-of-function Na+ channel abnormality, in contrast, results in the increase in late INa, which can lead to prolongation of APDs, EADs, reverse mode NCX transport, and subsequent Ca2+ overload in sarcomere, all of which predispose to ventricular arrhythmias. ROS have been demonstrated to affect Na+ channel function through multiple mechanisms. Transcriptionally, ROS have been shown to reduce Nav1.5 channel expression by reducing mRNA expression. At the protein level, ROS have been shown to impair Nav1.5 channel inactivation through direct oxidation at the methionine residues of Nav1.5 channel protein. Elevated mitochondrial ROS are known to reduce peak INa by modifying Nav1.5 conductance through post-translational mechanisms without affecting cell surface expression of Nav1.5. The slowly inactivating component of Na+ current (late INa), on the contrary, is known to be augmented by ROS in cardiac myocytes. For example, increased H2O2 has been shown to increase the open probabilities of Na+ channel, leading to increased late INa and arrhythmogenic changes including prolongation of APDs, EADs, and cytosolic Ca2+ overload (Figure 5; Table 2). In addition to direct ROS-dependent effects on Na+ channels, ROS also modulate Na+ channel activities indirectly by altering membrane lipid environment or by activating signaling molecules, such as PKC or CaMKII. Elevated mitochondrial ROS activate PKC, for example, which may reduce peak INa by affecting Nav1.5 phosphorylation. ROS-induced CaMKIIb activation, on the contrary, has been shown to mediate H2O2-induced increases in late INa.

Increased myocardial oxidative stress is often associated with impaired cardiac metabolism. The cardiac NADH level, for example, is elevated during cardiac ischemia and cardiomyopathy, which leads to increased mitochondrial ROS production and reduced peak INa. Using a mouse model of non–ischemic cardiomyopathy, we have demonstrated recently that the cytosolic NADH and mitochondrial ROS levels are increased with cardiomyopathy, resulting in a cardiac peak INa reduction without
altered membrane Na⁺ channel protein expression levels. The reduced peak I_{Na} can be restored by mitochondrial antioxidants NAD⁺ or Mito-TEMPO [(2,2,6,6-Tetramethylpiperidin-1-yl) oxyl] treatment. Consistent with these findings, NAD⁺ treatment has been shown to improve myocardial conduction abnormality that is associated with reduced peak I_{Na} in human failing heart.

The link between mitochondrial ROS and I_{Na} regulation is also observed in the hereditary arrhythmia syndromes. One of the Brugada syndrome–causing mutations, A280V mutation in glycerol-3-phosphate dehydrogenase 1–like protein, has been shown to increase peak I_{Na} by increasing cytosolic NADH levels and mitochondrial ROS. Peak I_{Na} reduction by A280V glycerol-3-phosphate dehydrogenase 1–like is abrogated by the treatment of NAD⁺ or Mito-TEMPO. Taken together, these data suggest the important role of mitochondrial ROS in transducing the altered cardiac metabolic states (NADH/NAD⁺ levels) to the regulation of cardiac Na⁺ channels and membrane excitability.

During acute ischemia, myocardial NO’ production is enhanced owing to increased NOS (especially eNOS) activity and conversion of tissue nitrate to NO’. Increased NO’ production and elevated NOS activities play a critical role in the cardioprotective effects of IPC (see Myocardial ROS and Potassium Channels Section of this article), which has been extensively reviewed previously. Elevated NO’ has been shown to increase late I_{Na} which can be abolished by reducing agents glutathione and DTT, suggesting that NO’ modulates Na⁺ channel activities by oxidizing Na⁺ channel or its regulatory proteins. Interestingly, others report that NO’ decreases peak I_{Na} through reducing the open probability and the surface expression of functional Na⁺ channels, which are mediated indirectly through a PKG/PKA-dependent pathway. Peroxynitrite, formed by NO’ and O₂⁻ interaction, has also been shown to augment late I_{Na}.

**Cardiac Redox State and Ca²⁺ Homeostasis**

As mentioned earlier in this review, intracellular [Ca²⁺] is tightly regulated by various Ca²⁺–handling proteins, including voltage-gated Ca²⁺ channels, SERCA, RyR2, NCX, and signaling molecules such as CaMKII, PKA, and PKC. Many of these Ca²⁺–handling and regulatory proteins harbor methionines or thiol groups that are susceptible to the direct modification by ROS or reducing agents, thereby sensitive to the altered redox states during cardiac diseases.

In general, elevated ROS levels in cardiac myocytes is known to result in a net increase in intracellular [Ca²⁺]. The direct application of H₂O₂ or increased mitochondrial ROS has been shown to increase I_{CaL} and its sensitivity to isoproterenol stimulation in ventricular myocytes. In addition, oxidized low-density lipoprotein has been demonstrated to stimulate I_{CaL} through lysophosphatidylcholine-induced mitochondrial ROS. Nevertheless, there are conflicting reports showing reduced cardiac I_{CaL} in the presence of elevated oxidative stress. The discrepant findings in the effects of ROS on cardiac I_{CaL} may be explained by the differences in the experimental design, animal species, and type of ROS involved.

The results on the impact of increased oxidative stress on other Ca²⁺–handling proteins, in contrast, are more consistent. Excessive ROS increases the open probability of RyR2, enhancing the release of Ca²⁺ from SR. Calcium sparks from RyR2 are increased in response to photoactivated or chemical-induced mitochondrial ROS. In contrast to RyR2, SERCA activity is reduced on increased cardiac ROS, which can be, at least in part, attributed to reduced ATP supply for SERCA pump owing to mitochondrial dysfunction. Cardiac NCX, which normally extrudes Ca²⁺ from cytosol in exchange for Na⁺, has been shown to be activated in the reverse mode by increased oxidative stress, thereby increasing cytosolic [Ca²⁺].

![Figure 5. Effects of increased oxidative stress on cardiac ion channel/transporter function.](image-url)

Table 2; Figure 5). CaMKII is activated by ROS, and it is known to play a critical role in regulating calcium-handling proteins in response to increased cardiac oxidative stress. For example, activated CaMKII augments I_{CaL} by phosphorylating Cav1.2 channel subunit and increasing its open probability. Phosphorylation of RyR2 by CaMKII increases SR Ca²⁺ leak, promoting cytotoxic Ca²⁺ overload and delayed afterdepolarizations. Taken together, the net impact of increased oxidative stress
Physiologically, mitochondrial Ca$^{2+}$ is required for normal metabolism and drives Ca$^{2+}$ from cytosol into mitochondria.\textsuperscript{117,203} An important role in the regulation of Ca$^{2+}$ in cardiac myocytes is actually reduced (because accumulated cytosolic Na$^{+}$ depletion of SR Ca$^{2+}$ store, resulting in detrimental changes, such as arrhythogenic delayed afterdepolarizations and contractile dysfunction.

As discussed earlier in this review, mitochondria also play an important role in the regulation of Ca$^{2+}$ in cardiac myocytes. Increased oxidative stress is known to modulate mitochondrial [Ca$^{2+}$] by altering mitochondrial ion channel activities, contributing to the perturbation of cytosolic Ca$^{2+}$ homeostasis. For example, increased ROS during myocardial ischemia depolarize $\Delta \Psi_{m}$,\textsuperscript{202} forcing mitochondrial NCX into reverse mode and drives Ca$^{2+}$ from cytosol into mitochondria.\textsuperscript{117,203} Physiologically, mitochondrial Ca$^{2+}$ is required for normal ETC function and serves as a positive effector of OXPHOS. Ca$^{2+}$ overload, however, leads to increased mitochondrial ROS production through mechanisms including increased electron leakage,\textsuperscript{204,205} enhanced NO$^{•}$ production, which is known to inhibit complex IV and augment ROS production from complex III.\textsuperscript{206} and reduced cytochrome $c$–mediated respiration.\textsuperscript{207,208} In addition, pathological mitochondrial Ca$^{2+}$ overload has been shown to increase NO$^{•}$ and ROS production in cardiac myocytes.\textsuperscript{209} These data suggest a positive feedback loop between ROS-induced Ca$^{2+}$-overflow and Ca$^{2+}$-induced ROS production. Under pathological conditions, such as myocardial ischemia, cellular and mitochondrial [Ca$^{2+}$] increase, leading to increased ROS production. ROS overproduction induced by elevated mitochondrial [Ca$^{2+}$] results in further increase in mitochondrial Ca$^{2+}$ and ROS levels. The Ca$^{2+}$ load and ROS produced from this positive feed-forward loop can overwhelm the cellular capacity of ROS scavenging and Ca$^{2+}$ clearance, resulting in cellular damage and electric instability that predispose to ventricular arrhythmias and SCD.\textsuperscript{210} It is worth noting that during heart failure, mitochondrial Ca$^{2+}$ uptake/accumulation is actually reduced (because accumulated cytosolic Na$^{+}$ during heart failure inhibits mitochondrial Ca$^{2+}$ uptake via activation of mitochondrial Na$^{+}$-Ca$^{2+}$ exchanger),\textsuperscript{119,120} which also favors ROS production (by impairing mitochondrial energetics and oxidizing NAD(P)H).\textsuperscript{119,120}

NO$^{•}$ and peroxynitrite also play important roles in modulating cardiac Ca$^{2+}$ channel and Ca$^{2+}$-handling proteins. Increased NO$^{•}$ inhibits L-type Ca$^{2+}$ channel activity through increased S-nitrosylation\textsuperscript{211,212} and cGMP-PKG-dependent phosphorylation\textsuperscript{123} of Ca$^{2+}$ channel subunits, which may contribute to the cardioprotective effects of IPC by limiting Ca$^{2+}$ influx during ischemia.\textsuperscript{121} The effects of NO$^{•}$ on RyR2 is concentration dependent. Physiological NO$^{•}$ levels ($\approx 1 \mu$mol/L) do not affect RyR2 activity, whereas supraphysiological levels ($\geq 100 \mu$mol/L) inhibit RyR2 activity.\textsuperscript{214} Peroxynitrite, on the contrary, activates RyR2 by oxidizing its cysteine residues.\textsuperscript{214} SERCA2a, by contrast, is inhibited by peroxynitrite-mediated tyrosine nitration. PKA pretreatment can prevent the inhibitory effects of peroxynitrite on SERCA2a by inducing dissociation of phospholamban from SERCA2a.\textsuperscript{215}

### Myocardial ROS and Potassium Channels

Increased oxidative stress is known to inhibit repolarizing Kv currents including $I_{\text{K,}}$ and several delayed rectifier $I_{K}$, $I_{\text{Ks}},$ and $I_{\text{Kr}}$ in mammalian ventricular myocytes.\textsuperscript{216–218} These effects are reversible by raising cellular antioxidant glutathione levels.\textsuperscript{140,219} ROS have been shown to regulate Kv current expression by reducing the transcript/protein expression of the Kv channel subunits\textsuperscript{218} and by modulating the phosphorylation of these channel subunits through PKs such as PKA, PKC, or protein tyrosine phosphatases.\textsuperscript{220–222} Cardiac K$^{+}$ channels are also regulated by NO$^{•}$. It has been reported that NO$^{•}$ inhibits human cardiac Kv4.3 channel, thereby reducing the transient outward K$^{+}$ current $I_{\text{to}}$.\textsuperscript{223} NO$^{•}$ also blocks Kv1.5 channel through S-nitrosylation and the activation of cGMP/PKG pathway.\textsuperscript{224}

Myocardial ROS also regulates myocyte membrane excitability through sarcK$^{\text{ATP}}$ channels. During myocardial ischemia, fuel substrate deprivation and increased oxidative stress depolarize the mitochondrial network, leading to fluctuated

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### Table 2. Effects of Increased Oxidative Stress on Cardiac Ion Channel/Transporter Function and Arrhythmogenicity

<table>
<thead>
<tr>
<th>Channel/Transporter</th>
<th>Effects of ROS</th>
<th>Effects on Electric/Ionic Homeostasis</th>
<th>Proarrhythmic Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak $I_{\text{Na}}$</td>
<td>$\downarrow$</td>
<td>$\downarrow$ Na$^{+}$ influx</td>
<td>Slow conduction</td>
</tr>
<tr>
<td>Late $I_{\text{Na}}$</td>
<td>$\uparrow$</td>
<td>$\uparrow$ Na$^{+}$ influx, APD prolonged</td>
<td>EAD</td>
</tr>
<tr>
<td>$I_{\text{p}}$</td>
<td>$\downarrow$</td>
<td>$\downarrow$ K$^{+}$ influx, APD prolonged</td>
<td>EAD</td>
</tr>
<tr>
<td>$I_{\text{k}}$</td>
<td>$\downarrow$</td>
<td>$\downarrow$ K$^{+}$ influx, APD prolonged</td>
<td>EAD</td>
</tr>
<tr>
<td>$I_{\text{f}}$</td>
<td>$\downarrow$</td>
<td>$\downarrow$ K$^{+}$ influx, APD prolonged</td>
<td>EAD</td>
</tr>
<tr>
<td>$I_{\text{K1}}$</td>
<td>$\uparrow$</td>
<td>$\uparrow$ K$^{+}$ influx, APD shortened</td>
<td>Current sink, slow conduction</td>
</tr>
<tr>
<td>NCX</td>
<td>Reverse mode</td>
<td>Ca$^{2+}$ overload</td>
<td>DAD</td>
</tr>
<tr>
<td>Cx43</td>
<td>$\downarrow$</td>
<td>Impaired gap junction function</td>
<td>Slow conduction</td>
</tr>
<tr>
<td>SERCA</td>
<td>$\downarrow$</td>
<td>Ca$^{2+}$ overload</td>
<td>DAD</td>
</tr>
<tr>
<td>RyR2</td>
<td>$\uparrow$</td>
<td>Ca$^{2+}$ overload</td>
<td>DAD</td>
</tr>
<tr>
<td>Mito-NCX</td>
<td>Reverse mode</td>
<td>Ca$^{2+}$ overload</td>
<td>DAD</td>
</tr>
<tr>
<td>Mito-K$_{\text{ATP}}$</td>
<td>$\uparrow$</td>
<td>Mitochondrial K$^{+}$ influx</td>
<td>Protective, ischemic-preconditioning</td>
</tr>
</tbody>
</table>

APD indicates action potential duration; Cx43, connexin 43; DAD, delayed afterdepolarization; EAD, early afterdepolarization; $I_{\text{p}}$, delayed rectifier K$^{+}$ current; $I_{\text{K}}$, inwardly rectifying K$^{+}$ current; $I_{\text{K1}}$, ATP-sensitive K$^{+}$ current; $I_{\text{f}}$, transient outward K$^{+}$ current; Late $I_{\text{Na}}$, late Na$^{+}$ current; mito-K$_{\text{ATP}}$, mitochondrial ATP-sensitive K$^{+}$ current; mito-NCX, mitochondrial Na$^{+}$/Ca$^{2+}$ exchanger; NCX, Na$^{+}$/Ca$^{2+}$ exchanger; Peak $I_{\text{Na}}$, peak Na$^{+}$ current; RyR2, ryanodine receptor 2; and SERCA, sarco/endoplasmic reticulum Ca$^{2+}$-ATPase.

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Cardiac renin–angiotensin system (RAS) activity is increased on acute ischemia, contributing to the acute and chronic myocardial remodeling in response to ischemia.251,252 RAS activation is known to increase myocardial oxidative stress and downregulate ventricular gap junction protein connexin 43.253–255 Transgenic mouse models with enhanced cardiac RAS activity255,256 have high incidence of conduction abnormality, ventricular arrhythmias and sudden death owing to reduced cardiac connexin 43 and abnormal gap junction function.255,256 Using a transgenic mouse model of cardiac-restricted angiotensin-converting enzyme overexpression (ACE8/8),255 we have demonstrated that increased cardiac RAS activity leads to increased activity of cSrc, a redox-sensitive tyrosine kinase, by increasing cSrc phosphorylation at Tyr416, in the ventricular myocardium. The activation of cSrc leads to connexin 43 downregulation, impaired gap junction function, slowed cardiac conduction, and increased incidence of ventricular arrhythmias and SCD.35,257 The downregulation of connexin 43 and increased risk for arrhythmias in angiotensin-converting enzyme 8/8 mice are alleviated by pharmacological inhibition of RAS258 and cSrc.255 It has been shown that increased myocardial p-cSrc leads to connexin 43 reduction through the competition between p-cSrc and connexin 43 for the binding with zonula occludens-1, a scaffolding protein at the intercalated disk, resulting in connexin 43 destabilization and degradation.259 Elevated p-cSrc levels also impair gap junction function by phosphorylating connexin 43 at tyrosine residues.260 Using the same ACE 8/8 mouse model, we have also shown that cardiac mitochondrial ROS were markedly increased with enhanced RAS activity.35,257 Treatment with mitochondria-targeted antioxidant MitoTEMPO, but not with other types of antioxidants, decreases cSrc phosphorylation, preserves connexin 43 expression, improves gap junction function, and abolishes ventricular arrhythmias and SCD in ACE 8/8 mice.35 Although the clinical evidence suggests that exogenous antioxidants do not prevent SCD,261 these data support a role for ROS, and suppression of endogenous, mitochondria-specific ROS may be an effective therapeutic approach.

Mechanistically, we have recently demonstrated that enhanced RAS signaling increases S-nitrosylation of cardiac caveolin-1 (Cav1), an intrinsic inhibitor of cSrc, resulting in Cav1-cSrc dissociation and subsequent cSrc activation. Cav1 S-nitrosylation upon enhanced RAS signaling is mediated by increased Cav1-eNOS binding that is dependent on elevated mitochondrial ROS.262 Consistent with these findings, Cav1 knockout mice exhibit increased cSrc activation, reduced connexin 43 expression, myocardial conduction defect, and increased inducibility of ventricular arrhythmias.262 Taken together, these data suggest the critical roles of mitochondrial oxidative stress and Cav1 in AngII–induced gap junction remodeling and arrhythmia. As mitochondrial ROS are increased in myocardial ischemia251,252 and heart failure,56,57 both of which are associated with RAS activation, reduced ventricular connexin 43 and increased risk for ventricular arrhythmias and SCD, it would be of great interest to test whether the treatment with mitochondria-targeted antioxidant

ΔΨ\textsubscript{m} and ATP production levels, which result in oscillation of sarcKATP currents and APDs.60,225 The ΔΨ\textsubscript{m} depolarization of the mitochondrial network is potentiated by widespread ROS production induced by focal increases in mitochondrial ROS (ROS-induced ROS release).61,62,226 IMAC plays a critical role in ΔΨ\textsubscript{m} depolarization on increased ROS; pharmacological inhibition of IMAC has been shown to prevent ΔΨ\textsubscript{m} depolarization and the oscillation of sarcK\textsubscript{ATP} currents and APD,59 as well as preventing ventricular arrhythmias in mammalian hearts227,228 during myocardial ischemia.

Another group of K\textsubscript{ATP} channels, residing on the mitochondrial inner membrane (mito-K\textsubscript{ATP} channels), contribute importantly to the protective effects of IPC, an endogenous cellular protective mechanism involving brief periods of ischemia that confers protection against infarction produced by a subsequent prolonged ischemia.148,229 Under physiological conditions, mito-K\textsubscript{ATP} channel opening enhances mitochondrial ROS production, triggering downstream signaling pathways involved in gene transcription and cell growth.230 During IPC, the activation of mito-K\textsubscript{ATP} channels allows mitochondrial K\textsuperscript{+} influx, resulting in partially depolarized ΔΨ\textsubscript{m}, which leads to a compensatory increase in proton pumping and cellular respiration to maintain ΔΨ\textsubscript{m} and ETC activity.229 Partially dissipated ΔΨ\textsubscript{m} induced by mito-K\textsubscript{ATP} channel opening blunts mitochondrial Ca\textsuperscript{2+} accumulation during ischemia and reduces PTP opening on reperfusion,231,232 both of which contribute to the protection against cell death by IPC. The opening of mito-K\textsubscript{ATP} channel also triggers the production of protective ROS, which activates a PKC-dependent pathway that confers cardiac protection by reducing deleterious postischemic ROS production.233,234 Interestingly, NO\textsuperscript{−}, a physiologically important free radical, has been shown to potentiate mito-K\textsubscript{ATP} opening235 and triggers both early and delayed IPC.236,237 In addition, mito-K\textsubscript{ATP} opening during ischemia provides additional K\textsuperscript{+} influx to maintain mitochondrial volume, which is critical to maintain the normal function of mitochondria and ETC.230 Pharmacological inhibition of mito-K\textsubscript{ATP} channels abrogates the antiarrhythmic effects of IPC,238 and several mito-K\textsubscript{ATP} channel openers are shown to provide protective effects against ischemia-induced cardiac arrhythmias.157,239,240

Mitochondrial ROS and Cardiac Gap Junction Regulation

Cardiac gap junctions are formed by the assembly of a pair of juxtaposed intercellular hemichannels with each hemichannel consisting of 6 connexin (connexin) proteins. Gap junctions mediate the intercellular communication of small metabolites and ions and play an essential role in cardiac electric conduction.241 Among the 3 principal connexin isoforms (connexin 40, connexin 43, and connexin 45) expressed in the heart, connexin 43 is the predominant isoform expressed in ventricular myocardocytes.242 Ventricular connexin 43 expression has been shown to be downregulated with myocardial ischemia,243,244 and heart failure,245,246 which can lead to slowed conduction, increased electric heterogeneity and abnormal anisotropic properties of the ventricles.247,248 These changes can facilitate the initiation and maintenance of ventricular arrhythmias and SCDs.249,250

\[ \Delta\Psi_m \text{ and ATP production levels, which result in oscillation of sarcK}_{\text{ATP}} \text{ currents and APDs.60,225 } \]
\[ \text{The } \Delta\Psi_m \text{ depolarization of the mitochondrial network is potentiated by widespread ROS production induced by focal increases in mitochondrial ROS (ROS-induced ROS release).61,62,226 } \]
\[ \text{IMAC plays a critical role in } \Delta\Psi_m \text{ depolarization on increased ROS; pharmacological inhibition of IMAC has been shown to prevent } \Delta\Psi_m \text{ depolarization and the oscillation of sarcK}_{\text{ATP}} \text{ currents and APD,59 as well as preventing ventricular arrhythmias in mammalian hearts227,228 during myocardial ischemia.} \]
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can normalize connexin 43 expression and prevent ventricular arrhythmias and SCD in these pathological conditions.

**Effects of Chronic Versus Acute Metabolic Derangement and Oxidative Stress on Arrhythmogenicity**

In this review, we have primarily focused on the impact of acute myocardial metabolic and oxidative stress on cardiac electrophysiology, arrhythmogenicity, and SCDs. It is important to note that chronic conditions associated with metabolic derangements and excessive oxidative stress such as aging, hypoxia/obstructive sleep apnea, chronic kidney disease, and diabetes mellitus also result in arrhythmogenic changes that predispose to SCDs. Many of the arrhythmogenic changes related to these chronic conditions involve electric remodeling and the creation of arrhythmogenic substrates such as fibrosis, which may not be seen with acute metabolic and oxidative stress. Nevertheless, the effects of acute and chronic metabolic/oxidative stress on cardiac electric function may not be mutually exclusive. The acute application of mitochondria-targeted antioxidant, for example, can restore the reduced peak $I_{Na}$ observed with chronic heart failure. In addition, reduced $K^+$ currents in diabetic heart can be reversed by acute insulin treatment. These observations suggest the contribution of the acute, modifiable metabolic/oxidative stress in these chronic conditions, which can be rapidly reversed by targeting the underlying metabolic/oxidative derangement. It is difficult to distinguish whether acute metabolic/oxidative changes exacerbate and amplify chronic changes or whether acute changes are unrelated to the chronic changes and simply occur on an arrhythmogenic background. Additional studies are required to address these possibilities.

**Conclusions**

In summary, metabolic derangement and increased oxidative stress are prevalent in arrhythmogenic cardiac conditions, particularly during myocardial ischemia. Impaired cardiac metabolism and increased ROS production can lead to malfunction of various cellular mechanisms that are required to maintain normal electric functioning and intracellular ionic homeostasis in cardiac myocytes. The impact of altered cardiac metabolism and increased oxidative stress on cardiac arrhythmogenicity is summarized in Table 1, Figure 4 and Table 2, Figure 5, respectively. Because the conventional antiarrhythmic drugs targeting ion channels are often proarrhythmic, understanding the mechanisms linking abnormal metabolism and oxidative stress to cardiac arrhythmias may help to develop novel therapeutics to reduce the risk of life-threatening arrhythmias and SCD in patients with cardiac diseases. These observations suggest that therapeutics tailored to ameliorate metabolic derangement and oxidative stress may prove a more efficacious alternative to traditional ion channel blocking drugs to address arrhythmia in associated with cardiac diseases, and a list of potential novel therapeutics are summarized in Table 3.

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**Disclosures**

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