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Cardiac voltage-gated ion channels in safety pharmacology: Review of the landscape leading to the CiPA initiative

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Abstract
Voltage gated ion channels are central in defining the fundamental properties of the ventricular cardiac action potential (AP), and are also involved in the development of drug-induced arrhythmias. Many drugs can inhibit cardiac ion currents, including the Na⁺ current (I\textsubscript{Na}), L-type Ca\textsuperscript{2+} current (I\textsubscript{Ca-L}), and K⁺ currents (I\textsubscript{to}, I\textsubscript{k1}, I\textsubscript{k5}, and I\textsubscript{Kr}), and thereby affect AP properties in a manner that can trigger or sustain cardiac arrhythmias. Since publication of ICH E14 and S7B over a decade ago, there has been a focus on drug effects on QT prolongation clinically, and on the rapidly activating delayed rectifier current (I\textsubscript{Kr}), nonclinically, for evaluation of proarrhythmic risk. This focus on QT interval prolongation and a single ionic current likely impacted negatively some drugs that lack proarrhythmic liability in humans. To rectify this issue, the Comprehensive in vitro proarrhythmia assay (CiPA) initiative has been proposed to integrate drug effects on multiple cardiac ionic currents with in silico modeling of human ventricular action potentials, and in vitro data obtained from human stem cell-derived ventricular cardiomyocytes to estimate proarrhythmic risk of new drugs with improved accuracy. In this review, we present the physiological functions and the molecular basis of major cardiac ion channels that contribute to the ventricle AP, and discuss the CiPA paradigm in drug development.

Key words: Action Potential (AP), Action Potential Duration (APD), Cardiac voltage-gated ion channels, I\textsubscript{Na}, I\textsubscript{to}, I\textsubscript{k}, hERG, I\textsubscript{k5}, in-vitro study, cardiac action potential, early afterdepolarization (EAD), delayed afterdepolarization (DAD), cardiac arrhythmias, QT prolongation, torsade de pointes (TdP), patch clamp, comprehensive in-vitro proarrhythmia assay (CiPA)
1. Introduction

In this article we provide a comprehensive overview of major ion currents contributing to cellular cardiac electrophysiology. Its scope spans fundamental concepts and more advanced considerations. The context is drug-induced proarrhythmia liability. The latest initiative in this regard, CiPA, reflects the recognition that arrhythmia liability is determined by the interaction between the entirety of the cellular electrophysiology matrix, and not simply one current ($I_{Kr}$).

1.1 Principles of cardiac cellular electrophysiology

Voltage-gated ion channels are complex transmembrane spanning proteins that regulate a broad spectrum of physiological processes throughout the body (Hille, 1978) including excitability of neuronal, skeletal and cardiac muscle cells, as well as modulating contraction and relaxation. In the heart, prominent voltage-gated ion channels include sodium ($Na^+$), potassium ($K^+$) and calcium ($Ca^{2+}$) channels, and their inhibition by drugs can lead to serious adverse effects. KCNH2 gene codes for the Kv11.1 channel, known as the human Ether-a-go-go-Related Gene (hERG), which carries the delayed rectifier potassium current, $I_{Kr}$, a key component of repolarization during the cardiac action potential (AP). Blockade of $I_{Kr}$ delays cardiac repolarization, prolonging AP duration (APD) and the QT interval on the ECG, and potentially increases the risk for the development of the cardiac arrhythmia, Torsades de Pointes (TdP). Because of the historical association of drug induced $I_{Kr}$ inhibition with TdP, along with the regulatory emphasis on this current, the screening of drugs for effects on additional ventricular ionic currents has been largely disregarded in drug safety testing paradigms, despite well characterized roles in the cardiomyocyte AP (Pugsley et al., 2015).
1.2 Structure of voltage-gated ion channels

Voltage-gated Na\(^+\) and Ca\(^{2+}\) channels consist of a principal pore-forming \(\alpha\)-subunit and various accessory subunits. The \(\alpha\)-subunit of the Na\(^+\) channel is approximately 260 kDa, and its function is regulated by one or more auxiliary \(\beta\)-subunits (\(\beta1-\beta4\)) (Figure 1A). Voltage-gated Ca\(^{2+}\) channels are formed by a group of subunits, including a pore-forming \(\alpha\)-subunit (\(\alpha1\)) and at least two accessory subunits \(\alpha2\delta\) and \(\beta\) (Bodi et al., 2005). The voltage-gated Ca\(^{2+}\) channel \(\alpha\)-subunit (Figure 1B) is structurally similar to that of the Na\(^+\) channel (Catterall & Swanson, 2015).

All \(\alpha\)-subunits of the Na\(^+\) and Ca\(^{2+}\) channels comprise four homologous domains (DI-DIV), each of which contains six transmembrane segments (S1-S6). Domains DI-DIV are connected by cytoplasmic linkers. Segments S5 and S6 in each domain are connected via a hairpin-like P (pore) loop that lines the outer pore of channels (Gellens et al., 1992; Terlau & Stuhmer, 1998). In the pore-region of the Na\(^+\) channel \(\alpha\) subunit, an Asp-Glu-Lys-Ala (DEKA) motif determines Na\(^+\) selectivity. In the Ca\(^{2+}\) channel \(\alpha\) subunit four glutamate residues, known as the EEEE motif, are responsible for Ca\(^{2+}\) selectivity. The S4 segment in each domain contains positively charged amino acid residues and acts as a voltage-gated sensor by moving across the membrane to trigger channel activation, in response to membrane depolarization (Yang et al., 1996; Jiang et al., 2003). The short cytoplasmic intracellular loop connecting domains III and IV in Voltage-gated Na\(^+\) channel is thought to be the inactivation gate, which bends back into the channel and blocks the pore from the inside during sustained depolarization of the membrane (Stuhmer et al., 1989; Patton et al., 1992). The inactivation gate is located in the center of a DIII-IV linker with a three-amino-acid stretch, consisting of isoleucine, phenylalanine, and methionine (IFM) (West et al., 1992). Residues of the S6 segment in each domain often provide the binding site
for various drugs (e.g., local anesthetics), and contribute to the formation of the internal vestibule in the P-region. The amino (N)- and carboxy (C)- termini of the α-subunits are located on the intracellular side of the Na\(^+\) and Ca\(^{2+}\) channels, so as to act as the loops that connect the repeats of the core motif (Ragsdale et al., 1994).

K\(^+\) channels can be classified into three main groups depending on their pore-forming channel structures (Figure 1C). The first group includes the voltage-dependent K currents (K\(_v\)) derived from six families of channel proteins based upon D. melanogaster nomenclature. K currents included in this group include the transient outward K\(^+\) channel, Ca\(^{2+}\)-activated K\(^+\) channels and KCNQ channels, all of which form tetrameric structures comprised of subunits with six transmembrane segments (S1-S6) and cytoplasmic N- and C-termini. The S1-S4 segments move in response to voltage changes, functioning as the voltage sensor for the channel. The glycine-tyrosine-glycine (GYG) motif in the pore region is the critical sequence responsible for K\(^+\) selectivity (Snyders, 1999). The second group of K\(^+\) channels consists of two transmembrane segments (S1-S2), conducting three inward K\(^+\) currents: the inward-rectifying K\(^+\) (K\(_{ir}\)) channels, ATP-sensitive K\(^+\) (K\(_{ATP}\)) channels and G protein-coupled inwardly-rectifying K\(^+\) (GIRK) channels. The S1 and S2 segments are connected by a pore-forming P-loop. Cytoplasmic N- and C-termini are similar to the S5, S6 segments in the first group of K\(^+\) channels (Loussouarn et al., 2002). The third group of K\(^+\) channels is the most abundant group with more than 50 members all of which a have two-pore (P1 and P2) structure with four transmembrane segments (S1-S4) (Rasmusson et al., 1998; Kuang et al., 2015).
1.2.1 Voltage-gated Sodium (Na$^+$) channels

Ten genes encode the distinct Na$^+$ channel α-subunit isoforms (Nav1.1-Nav1.9 and Nax). Nav1.1-Nav1.9 isoforms are voltage-dependent channels, whereas Nax (encoded by the SCN7A gene), expressed in glial cells within the brain is Na$^+$ concentration-dependent; however, it is not homologous to other Na channels and does not exhibit voltage-sensitivity (Noda & Hiyama, 2015) (Table 1). The Na$^+$ channel isoforms are further characterized pharmacologically by their sensitivity to the specific neurotoxin, tetrodotoxin (TTX). The TTX-sensitive (TTX-S) isoforms (e.g. Nav1.1-1.4, Nav1.1.6 and Nav1.7) are blocked by nanomolar concentrations of TTX, whereas on the other hand, the TTX-resistant (TTX-R) isoforms (e.g. Nav1.5, Nav1.8 and Nav1.9) are blocked only by micromolar concentrations of TTX. Homologous residues, C374 in rNav1.5 and C373 in hNav1.5, confer resistance to TTX in the rat and human isoforms, respectively (Heinemann et al., 1992).

Cardiac voltage gated Na$^+$ current ($I_{Na}$) properties can be characterized by studying Nav1.5 channels recombinantly expressed in mammalian cells using the whole cell patch-clamp technique. $I_{Na}$ typically activates within 200-300μs and inactivates completely within 2-5 ms. $I_{Na}$ is an inward current characterized by a half maximum activation voltage ($V_{1/2}$) of approximately -50 mV to -55 mV, and inactivation $V_{1/2}$ of approximately -90 mV to -95 mV. Compounds that inhibit $I_{Na}$ include Class I arrhythmic agents (Milne et al., 1984), various peptide toxins such as TTX (Heinemann et al., 1992) and ranolazine (Zygmunt et al., 2001). The “late” component of $I_{Na}$ has received increased attention over the last few years and is emerging as an important contributor to the cardiac APD (Saint, 2009). It is potentially involved in defining rate-dependent adaption of ventricular repolarization and reverses use-dependence of QT.
prolonging agents (Guo et al., 2011). Late $I_{\text{Na}}$ may result from a time-invariant Na$^+$ “window current” (the overlap of $I_{\text{Na}}$ activation and inactivation voltage-dependent curves), steady-state $I_{\text{Na}}$ or the slowly inactivated portion of $I_{\text{Na}}$ (Noble & Noble, 2006; Zaza et al., 2008; Moreno & Clancy, 2012). In the ventricle, the late $I_{\text{Na}}$ is small, only accounting for around 0.5% of the peak amplitude of the fast Na$^+$ current. Its existence has been proposed for decades (Saint, 2008). While its physiological role has yet to be fully defined, it has similar biophysical properties to the fast Na$^+$ channel including ion channel selectivity and single channel conductance properties, but the population that constitute the late channels fail to inactivate after opening (Saint, 2008). In contrast to fast $I_{\text{Na}}$, a selective and specific blocker of late $I_{\text{Na}}$ is still not available. However some studies showed that the late current is pharmacologically distinct and appears sensitive to block by tetrodotoxin (TTX) and lidocaine as well as ranolazine (Ju et al., 1992; Saint et al., 1992). The magnitude of the late Na$^+$ current in the normal heart is small; however, its magnitude is increased in many pathologic conditions including ischemia (Zaza et al., 2008), heart failure (Pourrier et al., 2014) and congenital long QT syndrome type 3 (LQT3) (Wang et al., 1996). This late $I_{\text{Na}}$ component is thought to maintain the AP plateau (Ju et al., 1992; Saint et al., 1992; Saint, 2008; Zaza et al., 2008). However, when increased, it can prolong the period of ventricular repolarization and drive the Na$^+/\text{Ca}^{2+}$ (NCX) exchanger in reverse mode leading to an elevated intracellular Ca$^{2+}$ concentration thereby further increasing the risk of generating cardiac arrhythmias (Belardinelli et al., 2006; Noble & Noble, 2006).

1.2.2 Molecular basis of cardiac (Nav1.5) channels

Nav1.5 is expressed in the heart, particularly in the intercalated discs (Cohen, 1996; Agullo-Pascual et al., 2014). However, Nav1.5 channels are also found within the brain (Hartmann et
al., 1999; Donahue et al., 2000), the gastrointestinal tract (Ou et al., 2002), and neonatal skeletal muscle (Kallen et al., 1990). Nav1.5 is encoded by the SCN5A gene, located on chromosome 3q21-24. The gene consists of 28 exons spanning approximately 80 kb. It is 2,016 amino acids in length and has a calculated molecular weight of 227 kDa (Rogart et al., 1989; Gellens et al., 1992). There have been two alternatively spliced gene variants identified, termed Nav1.5c and Nav1.5d. However, Nav1.5c contains 2,015 amino acids and no glutamine at position 1077, thus it is also called Q1077del while Nav1.5d consists of 2,016 amino acids containing a glutamine (Q) at position 1077, and therefore it is called Q1077. mRNA studies from the human heart showed the presence of both variants, with levels of Q1077del/Nav1.5d being twice those of Q1077/Nav1.5c, in all heart specimens studied (Makielski et al., 2003; Tan et al., 2005; Camacho et al., 2006). Thus, in the human heart, alternative splice variants (Q1077del and Q1077) may interact with other SCN5A mutations, and cause variable biophysical phenotypes that could result in development of various heritable arrhythmias (Tan et al., 2005).

Six groups of β-subunits (β1-β4, β1A, β1B) have been identified in cardiac myocytes with different expression levels. β1 is localized to the intercalated discs and T-tubules in the heart, β3 to the T-tubules, and β2 and β4 to the intercalated discs (Dhar Malhotra et al., 2001; Maier et al., 2004). The β1 subunit is non-covalently associated with the α-subunit and regulates Na⁺ current amplitude and the kinetic rate of activation and inactivation of the channel; thus, it has a key role in interacting with the α-subunit of the Na⁺ channel compared with the multiple other β-subunits. It has been hypothesized that Na⁺1.5 channels initiate and propagate cardiac APs from one myocyte to the next at intercalated discs, but that β-subunits interact with
different Na⁺ channel isoforms regulating the properties of Na⁺ channels in discretely different ways in the different areas of the heart (Catterall et al., 2003).

1.2.3 Voltage-gated Calcium (Ca²⁺) channels

There are five types of Ca²⁺ channels, L- (long lasting and large conductance), T- (transient-opening and small conductance), N- (neuron pre-synapse), P- (Purkinje cells), and R- (resistant to peptide toxins) types. The T-type and L-type Ca²⁺ channels are involved in key roles in the heart, contributing to automaticity, cardiac conduction, APs and excitation-contraction (EC) coupling. Ca²⁺ channels (Table 2) influence intracellular Ca²⁺ homeostasis and its consequences, in addition to playing a role in electrogensis and conduction. In diastole, the intracellular Ca²⁺ concentration is low (~10⁻⁸ M). Once Ca²⁺ enters the cell, it initiates a variety of signaling pathways depending on the cell type, including cardiac muscle contraction, release of hormones and neurotransmitters, activation of Ca²⁺-dependent enzymes, and gene transcription. Ca²⁺ channels are classified into three groups: Cav1, Cav2 and Cav3. The Cav1 group has four members (Cav1.1-Cav1.4), mediating L-type Ca²⁺ currents and each are specifically blocked by the dihydropyridine (DHP) class of calcium channel blocking (CCB) drugs (Hess et al., 1986). The Cav2 group includes three members (Cav2.1-Cav2.3) and give rise to the P, N and R type currents, respectively. The Cav3 group includes Cav3.1-Cav3.3 and mediates T type Ca²⁺ currents.

T-type Ca²⁺ channels are expressed in atria (Bean, 1985) and Purkinje fibers (Hirano et al., 1989) as well as in some pacemaker cells (Hagiwara et al., 1988). However, functional T-type Ca²⁺ currents have been difficult to demonstrate in human atrial myocytes. L-type Ca²⁺ channels are
expressed in all regions of the heart. Ca\textsuperscript{2+} entry into cardiac cells happens mainly through L-type Ca\textsuperscript{2+} channels, leading to Ca\textsuperscript{2+} release from the sarcoplasmic reticulum and contraction. \(I_{\text{Cal}}\) also plays a significant role in the initiation of cardiac arrhythmias through early afterdepolarization (EAD) related mechanisms (January & Riddle, 1989) and through mediating slow conduction in ischaemic myocardium (Curtis, 1990). Because of its importance, Cav1.2 will be further discussed in the next section.

### 1.2.4 Cardiac voltage gated Ca\textsuperscript{2+} current (\(I_{\text{Ca,L}}\))

During the generation of a cardiac AP, \(I_{\text{Ca,L}}\) is rapidly activated in a voltage- and time-dependent manner, and inactivates slowly. The kinetics of \(I_{\text{Ca,L}}\) activation are nonetheless slower than those of \(I_{\text{Na}}\), taking a few milliseconds to reach peak amplitude. \(I_{\text{Ca,L}}\) activates at membrane potentials within the voltage range of an AP plateau, in line with a steady-state activation curve ranging from -40 mV to +10 mV, with a \(V_{1/2}\) of around -10 to -5 mV (Bers & Perez-Reyes, 1999). Steady-state inactivation yields a \(V_{1/2}\) of -40 to -45 mV. Overlap of activation and inactivation voltage-dependent curves allows “window current” fall in the AP plateau voltage range, and therefore contributes to the mechanism for EAD generation (January & Riddle, 1989). \(I_{\text{Cal}}\) decreases to almost zero upon repolarization, when the channel responsible for the slow delayed rectifier K\textsuperscript{+} current, \(I_{\text{Ks}}\), opens and contributes increasingly to membrane repolarization (Barhanin et al., 1996). Therefore, the biophysical properties of \(I_{\text{Cal}}\) contribute, in part, to maintaining the plateau phase (Phase 2) of ventricular AP along with the Na\textsuperscript{+}/Ca\textsuperscript{2+} exchanger (NCX), the antiporter membrane protein that removes Ca\textsuperscript{2+} from cells. Importantly, Cav1.2 is the main route of the Ca\textsuperscript{2+} entry that triggers Ca\textsuperscript{2+} release from the sarcoplasmic reticulum (SR) via its effects on type 2 ryanodine receptors (RyR2). The intracellular Ca\textsuperscript{2+} concentration ([Ca\textsubscript{i}])
is consequently rapidly increased through a process of Ca\textsuperscript{2+} induced Ca\textsuperscript{2+} release. The increased [Ca\textsubscript{i}] binds to the myofilaments and initiates cardiac contraction (Bers, 2002). When intracellular Ca\textsuperscript{2+} concentrations reach millimolar concentrations (Lee \textit{et al.}, 1985; Hirano \textit{et al.}, 1989), a feedback mechanism leads to rapid inactivation of Cav1.2 and results in an acceleration of channel recovery from inactivation (Bers & Perez-Reyes, 1999). A prolonged plateau provides enough time for I\textsubscript{CaL} to recover from voltage- and Ca\textsuperscript{2+} -dependent inactivation, resulting in reactivation and increased inward currents that can further depolarize the cardiac membrane potential (January & Riddle, 1989; Ming \textit{et al.}, 1994). In addition, extra Ca\textsuperscript{2+} will be moved into the SR by Ca\textsuperscript{2+} pumps through sarcoplasmic reticulum Ca\textsuperscript{2+} ATPase (SERCA) pathway or extruded out of cells through the forward mode of the NCX (Lederer \textit{et al.}, 1990; Bers, 2002). The NCX current (I\textsubscript{NCX}) can generate an inward current at the end of repolarization and therefore may contribute to the APD. I\textsubscript{NCX} can be involved in EADs and delayed afterdepolarizations (DADs) (Nattel, 2002; Sipido \textit{et al.}, 2007).

1.2.5 Molecular characteristics of cardiac L-type Ca\textsuperscript{2+} channels

There are four subfamilies of voltage-dependent Ca\textsuperscript{2+} channel pore-forming α1 subunits, Cav1-Cav4; each subfamily has several family members or splice variants (Lacinova, 2005). Cav1.2 (or α1C) is the pore-forming α1 subunit of the cardiac L-type Ca\textsuperscript{2+} channel, and is encoded by CACNA1C. Cavβ2 is the most frequently expressed Cav β subunit in the cardiac L-type Ca\textsuperscript{2+} channel (Perez-Reyes \textit{et al.}, 1992). Cavβ2 is a cytosolic protein that binds to α1C via the DI and DII linker, increasing α1C expression and I\textsubscript{CaL} amplitude and modifying I\textsubscript{CaL} kinetics (Stotz \textit{et al.}, 2004). Functional Cav1.2 channel complexes also need another accessory subunit, Cavα2δ (Arikkath & Campbell, 2003). Co-expression of Cavα2δ with α1C gives rise to an increased I\textsubscript{CaL}
amplitude and accelerated activation and inactivation (Gurnett et al., 1996). The α1 isoform is the ligand-recognition site that determines the effects of drugs on each of the Ca\(^{2+}\) channels in the heart. The L-type Ca\(^{2+}\) channels possess high affinity, stereoselective-binding domains for channel blocking drugs, and it is the blockade of these Ca\(^{2+}\) channels in the heart that mediates the effects of L-type calcium antagonists on heart rhythm.

1.2.6 Voltage-gated Potassium (K\(^{+}\)) channels

Cardiac voltage-gated K\(^{+}\) channels play an essential role in AP repolarization and render the atrial and ventricular cell equivalent to a ‘potassium battery’ during diastole owing to the K\(^{+}\) transmembrane concentration gradient and the fact that the main current active during diastole is I\(_{K1}\). The contribution of individual K\(^{+}\) channels to repolarization can vary depending on a number of factors including channel density in different cardiac regions (atrial, ventricular, epicardium, endocardium, mid-myocardium, etc.). This section will focus on four K\(^{+}\) currents, namely I\(_{to}\), I\(_{Kr}\), I\(_{KS}\), and I\(_{K1}\).

1.2.7 Transient outward K\(^{+}\) channel (I\(_{to}\))

I\(_{to}\) is composed of two (fast and slow) currents, termed I\(_{to,fast}\) and I\(_{to,slow}\). I\(_{to,fast}\) displays faster gating properties, and contributes to Phase 1 repolarization in APs. In patch clamp studies I\(_{to,fast}\) current activates and inactivates rapidly when membrane potentials are depolarized to relatively positive potentials above approximately −30 mV. The activation and inactivation gating kinetics are time- and voltage- dependent (Greenstein et al., 2000). The time constant of activation of I\(_{to,fast}\) is in the order of milliseconds, whereas the inactivation can be described by tens to hundreds of milliseconds (Patel & Campbell, 2005). The activation V\(_{1/2}\) is ~+10 mV, while
the inactivation $V_{1/2}$ is around -35 mV in the ventricle (Nabauer et al., 1993; Han et al., 2000). $I_{to,fast}$ is a Ca$^{2+}$-independent current. $I_{to,slow}$ also shows similarly rapid activation and inactivation kinetics, but it recovers slowly from inactivation. Kinetics of recovery from inactivation show that the time constants are of ~30-100 ms for $I_{to,fast}$ and ~100-1000 ms for $I_{to,slow}$ (Giles & Imaizumi, 1988; Patel & Campbell, 2005). $I_{to,slow}$ is the small Ca$^{2+}$-activated component of $I_{to}$. $I_{to,fast}$ can be distinguished from $I_{to,slow}$ by differential sensitivity to the K$^+$ channel toxins Heteropoda toxins (HPTXs) and 4-aminopyridine (4-AP). HPTXs at nanomolar concentrations block $I_{to,fast}$ but not $I_{to,slow}$ (Sanguinetti et al., 1997). 4-AP blocks $I_{to,fast}$ in the closed state, but also blocks the open state of $I_{to,slow}$ in a use-dependent manner (Campbell et al., 1993). Three α-subunit isoforms have been identified in the $I_{to}$ family. Kv4.2, encoded by gene KCND2, is the major α-subunit contributing to $I_{to,fast}$ in rodents; however Kv4.3, encoded by KCND3, is the primary α-subunit for $I_{to,fast}$ in larger mammals such as dogs and humans (Nerbonne, 2000). Kv1.4 (encoded by KCNA4) displays channel gating kinetics and pharmacological properties similar to $I_{to,slow}$ (London et al., 1998; Patel & Campbell, 2005). In addition to the selective blocker 4-AP, $I_{to,fast}$ is inhibited by many other cardiac drugs including the class Ic antiarrhythmic drug flecainide, the class Ia drug quinidine, the class III drug ambasilide, and the class IV drug diltiazem. Quinidine, ambasilide and diltiazem inhibit $I_{to,fast}$ in the open state and in a frequency-dependent manner whereas flecainide, propafenone and the class IV drug nifedipine inhibit $I_{to,fast}$ in the closed state in a frequency-independent manner. Blockade of $I_{to,fast}$ can prolong or shorten ventricular repolarization depending on secondary changes in other currents, and by affecting plateau duration and voltage.
Kv4.2, Kv4.3 and Kv1.4 are pore forming α-subunits underlying cardiac $I_{\text{to,fast}}$ that belong to Kv channel Shaker-related subfamilies (Shaker Kv1.x, Shab Kv2.x, Shaw Kv3.x and Shal Kv4.x) (Snyders, 1999; Nerbonne, 2000). $I_{\text{to,fast}}$ can also interact with $I_{\text{CaL}}$ with the help of the Ca$^{2+}$ binding protein, KChAP, and thereafter affect the overall Ca$^{2+}$ entry, APD and EC coupling. In particular, KChAP promotes Kv4.3 expression and displays rectifier currents. In addition, DPP6 (dipeptidyl aminopeptidase-like protein 6) is another subunit of cardiac Kv4.3 which regulates $I_{\text{to,fast}}$ expression (Radicke et al., 2005). $I_{\text{to,fast}}$ density is significantly higher in the epicardium and mid-myocardium than in endocardium, and thus mediates the notch (i.e., classic spike and dome) morphology of APs in epicardial and M cells (Antzelevitch et al., 1999).

1.2.8 Delayed rectifier K$^+$ currents ($I_{\text{ks}}$ and $I_{\text{kr}}$)

$I_{\text{kr}}$ and $I_{\text{ks}}$ activate slowly because of a single voltage-dependent gate upon depolarization, and because they change the membrane conductance with a delay after a depolarizing voltage step, they are named “delayed rectifier” based on the original description of K$^+$ channels in axons by Hodgkin et al (1949). Functional cardiac $I_{\text{ks}}$ derive from the co-expression of pore-forming α subunits and accessory β subunits. The KCNQ1 gene encodes α subunits, whereas KCNE1 encodes β subunits. The pore-forming α-subunit underlying $I_{\text{kr}}$ is Kv11.1, also known as hERG encoded by KCNH2. $I_{\text{kr}}$ is regulated by accessory β subunits encoded by KCNE2 gene. The structure of Kv11.1 is similar to the $I_{\text{to}}$ α-subunit structure described in Figure 1C.

$I_{\text{ks}}$ and $I_{\text{kr}}$ are important outward currents contributing to Phase 3 repolarization of APs in most regions of the heart, but especially within the ventricles. Activation kinetics of $I_{\text{ks}}$ are relatively slower than those of $I_{\text{kr}}$. The corresponding time constant is in the order of seconds for $I_{\text{ks}}$, but
of tens or hundreds of milliseconds for $I_{Kr}$ (Cheng & Kodama, 2004). In addition, $I_{Ks}$ is activated at more positive membrane potentials than $I_{Kr}$, giving a steady-state activation $V_{1/2}$ value of approximately $+25$ to $+30$ mV for $I_{Ks}$, and $-10$ to $-20$ mV for $I_{Kr}$. The current-voltage (I-V) relationship of $I_{Ks}$ is linear due to an extremely slow inactivation processes (Mitcheson & Sanguinetti, 1999); whereas $I_{Kr}$ displays an inverted bell-shaped I-V relationship because of rapid inactivation, with current peaking at potentials ranging between 0 and $+10$ mV. The fast inactivation of $I_{Kr}$ at positive membrane potentials accounts for inward rectifying currents (Smith et al., 1996), which makes $I_{Kr}$ play an additional, albeit small, role in the AP plateau (Sanguinetti & Jurkiewicz, 1990). Inactivation is removed as cells repolarize making $I_{Kr}$ a key player in repolarization. $I_{kr}$ and $I_{Ks}$ are expressed in guinea pig, rabbit, dog and human ventricles, and are prominent repolarizing currents in these species. In adult rat and mouse ventricles, however, their densities are very low or undetectable, and the fast resting heart rate renders these currents non-functional even if the channels, or the gene homologues, are present.

Pharmacological tools can be used to distinguish $I_{Kr}$ from $I_{Ks}$. For example, when studying $I_K$ in guinea pig myocytes, $I_{kr}$ can be selectively blocked by some class III antiarrhythmic agents such as E-4031, dofetilide, and D-sotalol (Sanguinetti & Jurkiewicz, 1990; Tamargo et al., 2004), leaving a drug-resistant component that is $I_{Ks}$ (Sanguinetti & Jurkiewicz, 1990). $I_{Kr}$ can also be blocked by the class Ia-c antiarrhythmic agents quinidine, mexiletine and flecainide, respectively (Tamargo et al., 2004). In addition, non-cardiac-targeting drugs can also inhibit $I_{Kr}$ at therapeutic concentrations, leading to acquired QT prolongation described in section 4. $I_{Ks}$ is selectively blocked (compared with actions on other cardiac K currents) by chromanol 293B (Busch et al., 1996), the benzodiazepine L-735,821 (Jurkiewicz et al., 1996), the diuretic
indapamide (Turgeon et al., 1994) and the chromanol derivative HMR 1556 (Thomas et al., 2003). Most of the $I_{Ks}$ inhibitors act by blocking the channel in the activated state. The Ca$^{2+}$ channel blocker bepridil blocks the tail current of $I_{Ks}$ more potently with pulses shorter than 600 ms in an envelope protocol, therefore suggesting that the binding affinity to the channel is greater in the closed state (Yumoto et al., 2004), while chromanol 293B and L-735,821 block $I_{Ks}$ by binding to the pore region and S6 of the α subunits. T312 in the pore region and I337, P339, P340, and A344 in the S6 domain are key amino-acid residues contributing to KCNQ1 channel block (Seebohm et al., 2003).

1.2.9 Inward rectifier K$^+$ current ($I_{K1}$)

$I_{K1}$ contributes to Phase 3 repolarization, and plays a major role in setting the resting membrane potential in the heart. $I_{K1}$ conductance is greatest at potentials negative to the K$^+$ equilibrium potential ($E_K = -90$ mV), and is maintained because the channel possesses no inactivation gate (and therefore lacks time-dependent inactivation during diastole). $I_{K1}$ shows strong inward rectification, and is voltage-dependent, shifting in conformation to the rested state at positive potential. The rectification properties of $I_{K1}$ result from the fact that outward conductance is unidirectionally blocked by intracellular multivalent ions (especially Mg$^{2+}$) and polyamines including putrescine, spermidine and spermine (Nichols et al., 1996; Lopatin & Nichols, 2001). $I_{K1}$ density is greater in the ventricles than in the atria (Melnyk et al., 2002; Schram et al., 2002). The current can be inhibited by extracellular Ba$^{2+}$ and intracellular Cs$^+$, and relatively selectively by certain drugs that were developed as potential Class III antiarrhythmics such as RP58866 (Rees & Curtis, 1993). Note that unlike the K$V$ channels, K$ir$ channels lack an intrinsic S4 “voltage sensing element” and a mechanism for rapid N-type inactivation (i.e., inactivation that occurs
by the movement of the cytoplasmic N-terminus to the internal vestibule of the opened channel (Hoshi et al., 1991) and therefore do not “sense” and respond to changes in membrane potential in the manner of other Kv channels, as mentioned above. The Kir channels are nonetheless affected by membrane voltage (Pugsley et al., 2015).

Cardiac I\(_{K1}\) has three isoforms, which are encoded by three distinct genes: KCNJ2 (Kir2.1), KCNJ12 (Kir 2.2) and KCNJ4 (Kir2.3). K\(_{ir}\) channel pore-forming α-subunits display a S1-S2 structure, as described in Figure 1C. Kir2.1 is the most important subunit underlying I\(_{K1}\). Mutations in the KCNJ2 gene are linked to LQT7 (Andersen syndrome). KCNJ2 mutant channels have a compromised K\(_{ir}\) 2.1 function caused by a dominant-negative effect. Affected patients may have cardiac electrophysiological changes leading to life-threatening arrhythmias. Kir2.1 and Kir2.3 are expressed at higher levels in the ventricle than in the atrium (Melnyk et al., 2002; Schram et al., 2002).

2 The Cardiac Action Potential

Figure 2B demonstrates the different phases in an archetypal ventricular AP. Phase 4 describes the resting membrane potential (\(E_m\)), and has a voltage range of −80 to −90 mV. I\(_{K1}\) is a main current active in phase 4 in ventricular cells. During phase 4, Na\(^+\) and Ca\(^{2+}\) channels are in the rested state meaning that depolarization (triggered in working heart by electrotonic spread of the propagating AP from neighbouring cells) can trigger an AP owing to resultant voltage-dependent shifts to the activated state of these channels (positive feedback) when depolarization reaches the threshold for activation of the Na\(^+\) channels (at about −60 mV). In the sinoatrial node, the pacemaker current (I\(_{if}\)) which is a non-selective cation current activates
as a result of hyperpolarization, and initiates the propagating AP (Robinson & Siegelbaum, 2003). Elsewhere, phase 0 is the AP upstroke caused by Na\(^+\) channels opening. The maximum rate of depolarization during phase 0 (dV/dt\(_{\text{max}}\), where dV is the change of membrane potential voltage within the depolarisation interval dt\(_{\text{max}}\)) determines conduction velocity (Cohen et al., 1985). Phase 1 repolarization is characterized by the formation of a notch in the AP and is caused by fast time-dependent inactivation of I\(_{\text{Na}}\) and activation of I\(_{\text{to fast}}\). Phase 2 is the plateau that results from the opposing influences of inward (I\(_{\text{Ca-L}}\)) and outward (I\(_{\text{Kr}}\) and I\(_{\text{Ks}}\)) currents. Alteration of the amplitude of these currents can increase or decrease the APD and the QT interval. Phase 3 is repolarization, and is driven by I\(_{\text{Ks}}\), I\(_{\text{Kr}}\) and I\(_{\text{K1}}\) (Matsuura et al., 1987; Sanguinetti & Jurkiewicz, 1990). I\(_{\text{Ca-L}}\) is inactivated during phase 3 (Ono & Iijima, 2010). Finally, I\(_{\text{K1}}\) becomes activated towards the end of phase 3 (Bodi et al., 2005). NCX carries an inward current that is driven by the membrane potential at the terminal AP repolarization.

The morphology of cardiac APs has been shown to vary markedly between cardiac regions. For example, APs recorded from the sinoatrial (SA) and atrioventricular (AV) nodes display lower amplitudes and slow upstroke velocities when compared to ventricular tissue, reflecting the more positive E\(_{\text{m}}\) in diastole (phase 4) and the subsequent reduced contribution of Na\(^+\) current and increased contribution of Ca\(^{2+}\) to phase 0 in this tissue (Fig 2C). In the pacemaker cells of nodal tissues phase 4 is characterised by a slow steady spontaneous depolarization, named diastolic depolarization, that leads to a ‘threshold’ potential (TP), resulting in the all-or-none generation of APs, and pacemaker activity (Bers, 2008). This is due mainly to the presence of the non-selective pacemaker or ‘funny’ inward current (I\(_{\text{f}}\)), and a reduced contribution of I\(_{\text{K1}}\). Atrial APs show a shortened plateau phase and repolarize faster than ventricular cells (Figure
2C). In addition, the ultra-rapid delayed rectifier potassium current (\(I_{\text{kur}}\)) generated by the 
\(\text{Kv1.5}\) channel selectively contributes to phase 3 in human atrial APs (Nattel, 2002; Ruan et al., 2009).

2.1 Mechanisms of cardiac arrhythmias being studied

The surface electrocardiogram (ECG) is the main tool used to diagnose abnormal cardiac activity since each of the different segments and intervals represent the activity of specific ion channels in discrete regions of the heart. In humans, common causes of arrhythmias include myocardial ischemia, infarction, or reperfusion of a previously ischaemic myocardium. Most of these conditions can be readily reproduced \textit{in situ} and \textit{ex vivo} preparations, such as with Langendorff assays. While the pathology of arrhythmias may not appear to be relevant to the safety pharmacologist, our understanding of the underlying ionic mechanisms, based on decades of studies in numerous refined non-clinical models, has contributed to the development of the CiPA paradigm (see below) in its role of assessing the ‘proarrhythmia potential’ for a new drug. For a very comprehensive guide to the study of cardiac arrhythmias in humans and animals, see Curtis et al (Curtis et al., 2013).

The underlying causes of cardiac arrhythmias are normally inferred, since it is not possible to distinguish between re-entry, flow of injury current and abnormal automaticity in an intact human, or even an isolated perfused animal heart with any certainty. Indeed, abnormal automaticity is an event in a cell and requires single cell AP recording for verification. Moreover, unless captured during ECG recordings (i.e., after the patient has begun to receive medical assistance), the initiating mechanism underlying arrhythmias can never be determined
with certainty. Paradoxically this is most relevant to the most lethal arrhythmias, ventricular fibrillation (VF) and sustained TdP which commonly occur unobserved, and in the case of VF the first episode a patient experiences is usually lethal if first aid is not administered within 2-3 minutes of its onset. Unfortunately it is not possible to infer mechanisms of lethal arrhythmias by the controlled initiation or observation of spontaneously occurring nonlethal arrhythmias because the mechanisms, at least in animal models in which they can be studied, are different (Curtis et al., 2013).

2.1.1 Early and delayed afterdepolarization-induced arrhythmias

Early afterdepolarizations (EADs) occur during the repolarization phase of the AP (Binah & Rosen, 1992). They are precipitated by bradycardia or long cardiac pauses, allowing for APD prolongation and for sufficient time for $I_{Ca,L}$ to recover from inactivation, leading to reopening of calcium channels within the plateau range and the generation of inward current initiating EADs. In the setting of QT prolongation, a small number of Nav1.5 channels have been shown to also remain open within the plateau voltage, carried by the late $I_{Na}$ (Saint, 2009; Pugsley et al., 2015).

Delayed afterdepolarization (DAD) is abnormal depolarization interrupting phase 4 of the cardiac AP (Figure 3B) during diastole (Fozzard, 1992). DADs are dependent upon the duration of the diastolic interval but, unlike EADs, the amplitudes of DADs increase during tachycardia. DADs may result from an elevated cytosolic Ca$^{2+}$ concentration in circumstances where the cell’s capacity to regulate this is impaired. This may then trigger spontaneous Ca$^{2+}$ release from the SR during repolarization. This so-called setting of Ca$^{2+}$ overload may be accelerated by
digitalis toxicity, β-adrenoceptor stimulation and low extracellular K⁺. Digoxin toxicity can cause diastolic SR Ca²⁺ release, thereby initiating DAD events (Rosati et al., 2001), and this is likely to be exacerbated if there is additional underlying ryanodine receptor dysfunction. Such spontaneous Ca²⁺ release from the SR extrudes Ca²⁺ via the NCX and cardiomyocyte depolarization, eventually leading to DAD-induced triggered activity (Pogwizd et al., 1999). DAD events also induce ventricular tachycardia and fibrillation, but they are precipitated in the background of rapid heart rates (Priori et al., 1999).

2.1.2 Re-entrant mechanisms of arrhythmias

Although EAD and DAD mechanisms may account for the initiation of some arrhythmias (with the caveats outlined at the start of this section), the major (perhaps exclusive) mechanism that sustains ventricular arrhythmias is re-entry. Re-entry is failure of an impulse to self-terminate owing to the presence of regions of slow conduction that render separate parts of the wave front out of synchronization. The slower part of the wave front may then encounter adjacent tissue that has recovered excitability and may then propagate in this abnormal direction (through the adjacent tissue), re-entering the tissue it excited earlier – the hallmark of re-entrant arrhythmias (Figure 3C). Abnormalities in cardiac tissue (e.g., ischemia) can generate a tissue substrate for re-entry (Nattel, 2002) by changing conduction velocity or refractory period. Injury-induced conduction block facilitates re-entry by creating a region of ‘adjacent’ excitable tissue distal to the block, and an island of inexcitable tissue around which a re-entrant circuit may flow. This is exacerbated when the block is unidirectional, which is a feature of ischemia-induced injury in Purkinje fibres. Because the small fibres impinge on larger regions of ventricle there is a ‘sink-source mismatch’ and although conduction from Purkinje fibre to ventricle may
fail locally, conduction in the opposite direction may be permitted as a consequence of the larger current source when an ‘adjacent’ wave front propagates retrogradely from the large mass of ventricle into the smaller damaged fibre (Antzelevitch, 2001). Re-entry can occur in a single circuit, or multiple unstable re-entrant circuits simultaneously, producing more irregular activity such as multiple monomorphic or polymorphic ventricular tachycardia (VT) or VF (Binah & Rosen, 1992).

3 Heterologous expression systems: *in vitro* patch clamp electrophysiological studies

Mammalian cells are used as the principal host for cloned human ion-channel expression studies conducted within pharmaceutical drug development. The most common heterologous expression systems include human embryonic kidney 293 (HEK 293) cells and Chinese hamster ovaries (CHO) cells, both of which are used primarily in the conduct of drug safety pharmacology studies. These systems can be made to over-express ion-channels of interest, avoiding contamination by background or endogenous currents. Transient or stable expression of exogenous ion channel proteins in these host system is achieved using recombinant DNA technology. Although these expression systems generally yield consistent results, some inconsistencies have been highlighted between *Xenopus* oocytes and HEK 293 cells (Tan et al., 2003; Farrokhi *et al.*, 2009), in part because of the high level of protein binding that occurs in the oocytes related to the presence of the yolk leading to reduced apparent potency for some drugs and limiting our ability of determining their TdP liability.

Studies are usually conducted at room temperature or at physiological temperatures (~37°C). While temperature definitely affects channel kinetics, it does not appear to greatly influence
potency, with a few exceptions (Kirsch et al., 2004). Data obtained at either temperature can provide important information about drug actions.

4 Acquired long QT syndrome (aLQTs)

Certain classes of therapeutic drugs have an associated risk to cause acquired long QT syndrome (aLQTs) (Kannankeril et al., 2010). This syndrome represents one of the most critical potential side effects for clinical consideration since in certain instances it can lead to the potentially lethal arrhythmia, TdP. (Curtis et al., 2013). A wide range of drug classes have been shown to increase the QT interval, and for many, this is statistically associated with an increased risk of TdP including: antiarrhythmics, antihistamines, antibiotics, antimicrobials, antipsychotics, oncology agents and others (Table 3). Because of this, aLQTs has been used as a risk indicator for TdP (Curtis et al., 2013). Not all drugs that prolong the QT will cause TdP, not all patients with aLQTs will develop TdP, but by definition, all drugs that cause TdP have been shown to prolong the QT interval (Curtis et al., 2013). Drugs that prolong QT may be approved by FDA, some with a label restriction (e.g., ziprasidone). While most aLQTs is associated with direct inhibition of $I_{Kr}$, some drugs have been shown to affect hERG channel trafficking at the cell surface (Marzuillo et al., 2014).

4.1 Factors affecting TdP liability

Studies have suggested that pharmacological inhibition of $I_{Kr}$ leading to QT prolongation and TdP liability is typically mediated through binding to the S6 domain of the $\alpha$ subunit of the channel (Mitcheson et al., 2000). Drug exposure is a major factor affecting outcome. Like many others, the effects of terfenadine mediated QT prolongation, can be enhanced by the inhibition
of cytochrome (CYP) P450 3A4 – resulting in higher plasma concentrations (Jurima-Romet et al., 1994; Roden, 2004). Similarly, amiodarone (Ohyama et al., 2000) and cisapride (Desta et al., 2000) were also shown to increase plasma concentrations following CYP3A4 inhibition, resulting in a greater prolongation of the QT interval. Beyond exposure, multiple risk factors may exacerbate aLQTS or TdP risk, such as electrolyte imbalance (e.g., hypokalemia, hypomagnesemia, and hypocalcaemia), stroke, bradycardia, structural cardiac disease and congestive heart failure (Vos et al., 2001).

4.2 Drug-induced alterations in ion channel trafficking

 Trafficking of ion channels is the process by which newly synthesized proteins are transferred from the endoplasmic reticulum (ER) to the cell membrane, and later removed by the early endosome and degraded. Ribosomes produce nascent polypeptides, which are unfolded chains of amino acids critical for the ion-channel sequence (Curran & Mohler, 2015). Subsequently, these polypeptides are assembled and properly folded in the ER and Golgi apparatus. The fully synthesized ion-channel proteins are then sorted via the endosome and transported to the cell membrane where they are stably expressed. This is the anterograde trafficking pathway. It is balanced by a retrograde trafficking pathway via endosome and lysosome that downregulates channel density (Hwang, 2008; Johannes & Popoff, 2008).

 Drugs can alter $I_{Kr}$ expression by affecting different steps within the trafficking pathway (Cubeddu, 2016). Many drugs such as tricyclic antidepressants (Dennis et al., 2011), the selective serotonin reuptake inhibitor (SSRI) fluoxetine (Hancox & Mitcheson, 2006), the macrolide antibiotic erythromycin (Duncan et al., 2006) and theazole antifungal ketoconazole
(Takemasa et al., 2008) can affect trafficking. These drugs are thought to reduce channel density by inhibiting the transport of the fully mature channel protein from the ER to the membrane surface. Membrane I_{Kr} channel density has been shown to be decreased after long-term exposure to the chemotherapeutic medication arsenic trioxide, which has no direct inhibitory effects when perfused directly on to the channels (Drolet et al., 2004). Instead, arsenic trioxide was found to downregulate the chaperon complex formation in the trafficking pathway, resulting in the reduced availability of the channel for transport from the ER to the cell membrane (Ficker et al., 2004). The antimicrobial drug pentamidine has also been shown to slow the protein maturation process by directly altering the folding processes of I_{Kr} channels without affecting the chaperon complex (Kuryshev et al., 2005). Probucol, an anti-hyperlipidemic drug, increases I_{Kr} channel degradation in the trafficking pathway (Guo et al., 2007). These observations highlight the numerous mechanisms that are involved in channel trafficking and the limitations of in vitro drug safety screening that may not have scope for assessment of effects on trafficking. Furthermore, many of the drugs that affect trafficking also inhibit I_{Kr}, providing additive effects on AP prolongation.

5 The value of assessing the inhibition of multiple cardiac ion channels

The I_{Kr} assay plays a key role in helping to identify, early in the discovery process, compounds that have the propensity to prolong the QT interval through I_{Kr} inhibition. However, many compounds have inhibitory effects on multiple cardiac ion channels leading to complex alterations in the cardiac AP which may or may not translate into prolongation of the QT interval and/or a TdP liability. For example, the Class Ia antiarrhythmic drug, quinidine, is known to block multiple ion channels including I_{Na}, I_{CaL} and I_{Kr} as well as I_{Ks}, I_{K1}, I_{K-ATP} and I_{to}.
(Salata & Wasserstrom, 1988). However, despite this complex pharmacology it is used to restore normal sinus rhythm to patients with symptomatic atrial fibrillation/flutter, and to treat patients with life-threatening sustained ventricular tachycardia. At low therapeutic plasma concentrations, it can prolong the QT interval and potentially induce TdP (effects that may be related to its $I_{Kr}$ blockade); however, at elevated plasma concentrations, multiple ion channel block occurs and the potential QT-prolongation effects are reduced (Selzer & Wray, 1964; Ometto et al., 1990). Moreover, the Class IV antiarrhythmic drug, verapamil, has been shown to produce equipotent inhibitory effects on $I_{Cal}$ and $I_{Kr}$ (Zhang et al., 1999), but does not cause QT prolongation or increase risk of TdP because the effects on $I_{Cal}$ mitigate $I_{Kr}$ block, leading to limited changes in APD and TdP liability (Winters et al., 1985; Fermini & Fossa, 2003). Even if QT prolongation occurs, a drug does not necessarily have a notable TdP liability. For example, ranolazine (i.e. inhibition $I_{Kr}$ and $I_{Na}$) may cause QTc prolongation but have not been associated with TdP (Martin et al., 2006; Jia et al., 2011). Thus, proarrrhythmic effects emerge when the balance between inward and outwards currents is altered significantly. Because of the inherent difficulty in understanding and integrating the potential effects of compounds that affect multiple ion channels at similar concentrations, the use of logistic regression model may likely increase our ability to predict and translate, more efficiently, in vitro ion channel effects to in vivo outcomes, as proposed in the CiPA paradigm (Kramer et al., 2013; Colatsky et al., 2016).

5.1 Stem cells as a tool for proarrhythmia screening

There are two types of human stem cells: embryonic (ESC), which originate from fertilized eggs with the potential to differentiate into different tissues and organs, and adult pluripotent cells
of somatic origin, which have limited gene activation potential, but retain the ability to differentiate into only a few types of tissues. Induced pluripotent stem cells (iPSC) offer the potential to assess the risk of drug-induced proarrhythmia using a human derived model. The potential advantage is that it is possible to have an assay in which cells express a full range of ion channels as expressed in human ventricular myocytes. This approach is unique as cells can be differentiated to express not only normal, but also many variant cardiac disease phenotypes (e.g., LQTs (Moretti et al., 2010; Itzhaki et al., 2011; Malan et al., 2011; Egashira et al., 2012; Terrenoire et al., 2013), catecholaminergic polymorphic ventricular tachycardia (CPVT) (Yazawa et al., 2011), overlap syndrome of cardiac Na⁺ channelopathy (Davis et al., 2012) and arrhythmogenic right ventricular cardiomyopathy (ARVC) (Ma et al., 2013)). The potential for development of drug-induced arrhythmia may be evaluated by analyzing the parameters for each phase of the cardiac AP, as previously described. iPSC cardiac myocytes (iPSC-CM) are currently being investigated for use in drug safety ion-channel evaluations. iPSC-CMs can be cultured to obtain a large number of cells and can be used with manual or automated patch-clamp technology (Himmel, 2013; Mercola et al., 2013).

Currently, induced pluripotent stem cell-derived cardiomyocytes (IPSC-CMs) are being evaluated for their physiological similarity to adult human myocytes. At the moment, in terms of cardiac AP parameters, iPSC-CMs exhibit several distinct differences from adult human CMs. IPSC-CMs exhibit a less negative resting membrane potential when compared to adult ventricular myocytes (Ma et al., 2011; Davis et al., 2012). In addition, they show major differences in ion channel expression levels, especially for $I_{Kr}$ and $I_{f}$ (Khan et al., 2013). In general, the IPSC-CM phenotype currently used resembles that of a relatively immature CM and
exhibits a variable electrophysiological profile when compared to adult CMs (Himmel, 2013). Individual IPSC-CMs can exhibit either an atrial or ventricular AP morphology and many processes are being developed to enhance ventricular cell differentiation and selection for use in studies. As such, AP waveforms recorded from iPSC clusters presently tend to display heterogeneous phenotypes. Thus, it is imperative to improve selection of ventricular CMs for study, and further investigation is necessary in order to establish optimal in vitro study conditions for use in proarrhythmia screening.

5.2 CiPA: The next step in proarrhythmia assessment

The CiPA initiative is a consortium composed of a number of collaborators including, FDA, HESI, CSRC, Japan Nation Institute of Health Sciences (NIHS), Health Canada, European Medicines Agency (MEA), Pharmaceutical and Medical Devices Agency (PMDA, Japan), Japan iPS Cardiac Safety Assessment (JiSCA), academics, in silico modellers, and partners from contract research organizations, the pharmaceutical industry and device companies. The new paradigm, has the objective to engineer, early in the drug discovery and development process, assays allowing the evaluation of the proarrhythmic risk of compounds, instead of concentrating on their ability to inhibit the hERG current and to prolong the QT interval (Sager et al., 2014). This new paradigm is based on the fundamental mechanistic understanding of the role of ion channels in delayed ventricular repolarization, alterations to which lead to repolarization instability and arrhythmias. It is composed of two distinct nonclinical series of tests: 1) the in vitro study of drug effects on multiple ion channels (not just hERG), and incorporation of these effects in an in silico model of a human ventricular action potential (AP) in an effort to reconstruct the effects on ventricular repolarization and identify potential mechanism-based metrics that can assess
proarrhythmia risk, and 2) confirmation of *in silico* results using human ventricular myocytes, likely derived from human induced pluripotent stem cell (iPSC) cardiomyocytes (Fermini et al., 2016).

The *in silico* models will be built prospectively, using known torsadogenic drugs of varying risks. The iPSC-CM electrophysiology studies will be useful in confirming predictions based on the *in silico* model, as will phase I ECG studies in clinical trials should that data be available at the time of conduct of the CiPA assay. Additionally, ion channel inhibition protocols will be standardized, and will likely include multiple pharmacological endpoints. The *in silico* model will recapitulate the cardiac AP based on drug effects on these multiple ion channels and be aimed at determining potential (yet to be determined) proarrhythmia markers rather than just effects on APD alone. Drugs will be rank ordered for proarrhythmia risk. *In vivo* ECG analysis in both animals (SP CV studies) and humans (Phase I clinical trials) will play important roles in evaluating risk and confirming CiPA outcomes.

6 Conclusion

Proarrhythmia risk assessment for drug-induced TdP is constantly evolving. Over the years, cardiac ion channel testing emerged as an important tool for this. The proarrhythmia screening methodologies have migrated from an ‘hERG centric’ approach to a more integrated strategy including a broader spectrum of *in vitro* cardiac ion channel data, *in silico* modelling, *in vivo* studies and clinical trial data to protect later stage clinical trial participants and ultimately patients. The next decade of research in proarrhythmia risk assessments will require honing of the integrated risk assessment, now named CiPA, and validation of its component parts and the
way it is deployed to best effect. This may help avoid throwing ‘the baby out with the bath water’. The evolution of the CiPA methodology is certain to give rise to publications, propelled by increasing knowledge of drug effects on cardiac electrophysiology.

Conflict of Interest

None of the authors have any conflicts of interest, other than their employment in commercial pharmaceutical companies, academic institutions or contract research organizations. No information is presented in this paper that advocates for or promotes commercial products from any of our organizations.

Disclaimer

This article reflects the views of the author and should not be construed to represent FDA’s views or policies.
7 References

Reference List


*Circulation research* **85**, 1009-1019.

Pourrier M, Williams S, McAfee D, Belardinelli L & Fedida D. (2014). CrossTalk proposal: The late sodium current is an important player in the development of diastolic heart failure


Table 1. Some properties of voltage-gated Na⁺ channels

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CNS, Central nervous system; PNS, peripheral nervous system; TTX, Tetrodotoxin;

- The isoform of the Na⁺ channel is ‘sensitive’ if the channel is blocked at nM concentrations and resistant if blocked at µM concentrations
<table>
<thead>
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<td>unknown</td>
<td>Retina</td>
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<tr>
<td>P/Q</td>
<td>Ca,2.1 (α1A)</td>
<td>CACNA1A</td>
<td>α2δ, β</td>
<td>CNS (cerebellum)</td>
</tr>
<tr>
<td>N</td>
<td>Ca,2.2 (α1B)</td>
<td>CACNA1B</td>
<td>α2δ/β1, β2, β3,</td>
<td>CNS (brain) and peripheral</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>nerve system</td>
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<tr>
<td>R</td>
<td>Ca,2.3 (α1E)</td>
<td>CACNA1E</td>
<td>α2δ, β</td>
<td>CNS (cerebellum, neurons)</td>
</tr>
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<td>T</td>
<td>Ca,3.1 (α1G)</td>
<td>CACNA1G</td>
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<td>Heart (SA node), CNS</td>
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<td></td>
<td>(neurons), bone</td>
</tr>
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<td></td>
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<td>CACNA1H</td>
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<td>Heart (SA node), CNS</td>
</tr>
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<td></td>
<td></td>
<td>(neurons), bone</td>
</tr>
<tr>
<td></td>
<td>Ca,3.3 (α1I)</td>
<td>CACNA1I</td>
<td>unknown</td>
<td>CNS (brain)</td>
</tr>
</tbody>
</table>

CNS, Central nervous system; DPH, dihydropyridine

- The isoform of the Ca²⁺ channel is ‘sensitive’ if the channel is blocked at nM concentrations and resistant if blocked at μM concentrations.
Table 3. Drugs with an increased propensity for the development of QT prolongation and precipitation of Torsades de Pointes (TdP) arrhythmias

<table>
<thead>
<tr>
<th>Compound category</th>
<th>Compound</th>
<th>Compound category</th>
<th>Compound</th>
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<tbody>
<tr>
<td>Antiarrhythmic drugs (Class IA, Class III and Class IV)</td>
<td>Ajmaline</td>
<td>Anticancer drugs</td>
<td>Prenylamine</td>
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<td></td>
<td>Quinidine</td>
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<td>Arsenic trioxide</td>
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<td>Almokalant</td>
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<td>Terfenadine</td>
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<tr>
<td></td>
<td>Azimilide</td>
<td>Psychiatric Drugs</td>
<td>Amitriptyline</td>
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<tr>
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<td>Dofetilide</td>
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<td>Dronedarone</td>
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<td>Imipramine</td>
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<td>Antimicrobial drugs</td>
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<td>Trimethoprim-sulfamethoxazole</td>
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<td>Antimalarial drugs</td>
<td>Chloroquine</td>
<td>Others</td>
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<td>Halofantrine</td>
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<td>Domperidone</td>
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<td></td>
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<td>Cesium</td>
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Source: www.torsades.org; Woosley, RL and Romero, KA, www.Crediblemeds.org, QTdrugs List, [March 8, 2016], AZCERT, Inc. 1822 Innovation Park Dr., Oro Valley, AZ 85755]
Figure 1: A schematic view of the structure of voltage-gated Na\(^+\), Ca\(^{2+}\) and K\(^+\) channels. A) The Na\(^+\) channel \(\alpha\)-subunit is inserted into the lipid bilayer of the cellular membrane and constitutes the channel pore, through which Na\(^+\) ions pass. The subunit consists of four domains (DI-IV). Each domain contains six transmembrane segments. The pore is composed of segments S5-S6, while S4 acts as the voltage sensor. \(\beta\)-subunits have a single transmembrane segment, a long extracellular N-terminus, and a short intracellular C-terminus. B) The Ca\(^{2+}\)-channel \(\alpha_1\) subunit demonstrates a similar structural basis to the Na, channels. The \(\alpha_2\delta\) and \(\beta\) subunits enhance expression and modulate the voltage dependence and gating kinetics of the \(\alpha_1\) subunit. C) The K\(^+\)-channel \(\alpha\) subunit. The top panel shows voltage-dependent K\(^+\) -channel (Kv) \(\alpha\) subunits that contains six transmembrane segments (S1-S6) with one K\(^+\)-conducting pore. The middle panel shows inward-rectifying K\(^+\)-channel (Kir) \(\alpha\) subunits that contains two transmembrane segments with one pore region. The bottom panel shows the K2P model that contains four transmembrane segments with two pores.
Figure 2. The cardiac electrical conduction system and genesis of the cardiac action potential in fast-response and slow-response tissues. A) The basic cardiac structure and components involved in conduction of electrical impulses from the sinus node through the His-Purkinje system. B) A schematic of action potentials in fast-response and slow-response tissues. The bottom left panel demonstrates a typical morphology of a cardiac action potential in fast-response tissues (i.e., atrial and ventricular myocardium and Purkinje fibers). Each action potential comprises phase 0 through phase 4. Some channels may conduct in an inward or outward direction, depending on the membrane voltage at any given time point of the electrical cycle. Upright/downright arrows represent depolarizing and repolarizing currents, respectively. The bottom right panel demonstrates a cardiac action potential in slow-response tissue (i.e., the SA node and AV node).
Figure 3. Mechanisms underlying the development of cardiac arrhythmias. A) An early afterdepolarization (EAD)-induced action potential. B) Delayed afterdepolarizations (DAD)-triggered action potentials. C) Substrate of re-entry for ventricular arrhythmia development. The bottom left panel represents the normal conduction in a bifurcated pathway. The bottom middle panel indicates that electrical conduction is blocked in an area of refractory tissue (i.e., unidirectional block). The bottom right panel shows that if conduction velocity is slower than the tissue refractory period, then reentry can occur. See text for details.