Fundamental research conducted over the past 20 years has led to an explosion of knowledge on the genetic and molecular mechanisms that regulate the function of cardiac ion channels. One of the most important outcomes of such new understanding has been the realization that the traditional reductionist view that ionic currents are the expression of individual ion channels is misleading. Emerging evidence over the past 20 years strongly suggests that the normal electric function of the heart is the result of dynamic interactions of membrane ion channels working in an orchestrated fashion as part of complex molecular networks. Such networks work together with exquisite temporal precision to generate each action potential and contraction. Macromolecular complexes play crucial roles in transcription, translation, oligomerization, trafficking, membrane retention, glycosylation, post-translational modification, turnover, function, and degradation of all cardiac ion channels known to date. In addition, the accurate timing of each cardiac beat and contraction demands a comparable precision on the assembly and organization of sodium, calcium, and potassium channel complexes within specific subcellular microdomains, where physical proximity allows for prompt and efficient interaction. This review article, part of the Compendium on Sudden Cardiac Death, discusses the major issues related to the role of ion channel macromolecular assemblies in normal cardiac electric function and the mechanisms of arrhythmias leading to sudden cardiac death. It provides an idea of how these issues are being addressed in the laboratory and in the clinic, which important questions remain unanswered, and what future research will be needed to improve knowledge and advance therapy.


Key Words: arrhythmias, cardiac death, sudden, cardiac ion channels, multiprotein complexes
distinct proteins that are fixed and function independently expressed on an intracellular or surface membrane is no longer tenable. An ion channel protein may encounter and interact with hundreds of other proteins during its lifespan, from biosynthesis until degradation. Such a complex regulation over time and space suggests an important plasticity for these protein complexes which is a major determinant of cardiomyocyte function, including excitability, excitation–contraction coupling, intercellular communication, and the pathogenesis of arrhythmias. This article is part of the Circulation Research Compendium on Sudden Cardiac Death. It reviews research on many of the currently known multicomponent assemblies formed by the main cardiac ion channels with their protein partners. It looks also at the possible role that such assemblies may have in the molecular underpinnings of the normal electric function of the cardiomyocyte and the mechanisms of complex cardiac arrhythmias and sudden cardiac death (SCD). We are focusing on cis-interacting proteins, that is, within the same cell. Although there is emerging evidence for important roles of proteins, such as the β-subunits, of the voltage-gated sodium channels in transinteractions as cell-adhesion molecules, this aspect is not addressed in this review.

### Ion Channel Macromolecular Complexes

Macromolecular complexes consist of a handful to several thousand individual components, including proteins, nucleic acids, carbohydrates, and lipids, and perform a wide array of vital tasks in the cell. As such, they are essential to the proper functioning of all cellular processes, including metabolism, cell signaling, gene expression, trafficking, cell cycle regulation, and the formation of subcellular structures. In the cardiomyocyte, macromolecular complexes also play crucial roles in converting energy, generating and propagating electric signals, and mediating contractility, as well as intercellular communication. To achieve these functions, complex molecular networks work together with exquisite temporal precision to generate each AP and contraction. The accurate timing of the molecular events demands, in addition, a comparable precision on the location of each molecule within the cell. Indeed, molecular networks assemble and organize within specific subcellular microdomains, where physical proximity allows for prompt and efficient interaction. For example, Petitprez et al described 2 separate pools of (NaV1.5) sodium channels in ventricular cardiomyocytes. One subpopulation localizes at the lateral membrane of the myocytes, whereas the other localizes at the intercalated disc (ID), and a recent study has shown that NaV1.5 and potassium inward rectifier (Kir)2.1 colocalize at both the ID and the lateral membrane, which is important for mutual regulation and the control of cardiac excitability.

### Genetic Cardiac Channelopathies

Genetic cardiac channelopathies were identified >20 years ago. As of today, >35 distinct genes encoding ion channel subunits or regulatory proteins are known to be linked to arrhythmogenic syndromes. The estimated prevalence of cardiac channelopathies in the general population remains however difficult to assess. Cardiac channelopathies are likely responsible for about half of sudden arrhythmic cardiac death cases. The most prevalent genetic disorder is the congenital long-QT syndrome (LQTS). LQTS is caused by mutation-induced decrease in repolarizing currents or by increase in depolarizing currents. The second most frequent cardiac channelopathy is Brugada syndrome (BrS). The molecular mechanisms underlying BrS are still matter of controversy. Other important but more recently described forms of inherited arrhythmias caused by channel dysfunction include catecholaminergic polymorphic ventricular tachycardia, congenital short-QT syndrome, and mixed phenotypes.

### Sodium Channel Macromolecular Complexes

The main voltage-gated sodium channel expressed in cardiac myocytes is NaV1.5; it is encoded by the human gene SCN5A. NaV1.5 is a large pore-forming protein, also called α-subunit, with 2016 amino acids and of a molecular weight of ≈220 kDa (Figure 1). The NaV1.5 protein has been shown to assemble with small (≈30–40 kDa), single transmembrane segment proteins called β-subunits. Four of these β-subunits have been described in the human genome. The exact stoichiometry between the α- and β-subunits of the cardiac Na+ channels is not known. However, the brain α-subunit of the Na+ channels was copurified with 1 β1 and 1 β2-subunit suggesting a possible 1:2 α to β stoichiometry. Several hundreds of mutations in

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SCN5A have been linked to cardiac arrhythmic disorders, such as the congenital and acquired LQTS, BrS, conduction slowing, sick sinus syndrome, atrial fibrillation, and dilated cardiomyopathy. Importantly, mutations in the genes coding for some of these partner proteins were found in patients with genetic cardiac channelopathies, for example, congenital LQTS and BrS. The proteins interacting with Na\textsubscript{v}1.5 may have different functions such as anchoring/adaptor proteins involved in trafficking, targeting, and anchoring of the channel protein to specific membrane compartments; as enzymes interacting with and modifying the channel structure via post-translational modifications; and as proteins modulating the biophysical properties of Na\textsubscript{v}1.5 on binding. For further details see the recent review article.

Among the proteins that have been proposed to be involved in targeting the Na\textsubscript{v}1.5 channel proteins to specific compartments, α1-syntrophin (Figure 2A) and the membrane-associated guanylate kinase protein, synapse-associated protein 97 (SAP97), play crucial roles (Figure 1). Both proteins have PDZ (postsynaptic density protein [PSD95], Drosophila disc large tumor suppressor [Dlg1], and zonula occludens-1 protein [zo-1]) protein–protein interacting domains allowing the direct interaction with the 3 last C-terminal residues of Na\textsubscript{v}1.5 (serine–isoleucine–valine or SIV motif). Recent studies using genetically modified mouse models indicated a role of the syntrophin–dystrophin macromolecular complex and the key role of the SIV motif in determining the density of Na\textsubscript{v}1.5 channels at the lateral membranes of myocytes (Figure 3). Although the role of the SIV motif and SAP97 at the ID remains to be clarified, neither truncated channels (ΔSIV) nor the cardiac ablation of SAP97 were sufficient to perturb the expression of Na\textsubscript{v}1.5 at the ID of mouse cardiac cells (Figure 2A and 2B). Two other distinct protein–protein interacting domains are well recognized in the C-terminal sequence of Na\textsubscript{v}1.5 (Figure 1): the IQ (isoleucine-glutamine calmodulin binding motif)-motif allowing specific interaction with calmodulin and the PY (proline-tyrosine protein-protein interaction motif)-motif, a domain found in membrane proteins permitting the binding of ubiquitin ligases of the Neural precursor cell Expressed, Developmentally Downregulated 4 (Nedd4)/Nedd4-like family. Although the structural details and roles of the interaction of calmodulin and Na\textsubscript{v}1.5 have been controversial, a recent study suggested a model where calmodulin may be an essential molecular player in the transitions between the different channel states.

**Mutations in Genes Coding for Na\textsubscript{v}1.5 Channel–Interacting Proteins and Associated Disorders**

Among the long list of proteins interacting with Na\textsubscript{v}1.5 (Figure 1), mutations in the genes coding for 6 of them were reported in patients with altered electric function that may lead to SCD. Also important, >20 naturally occurring mutations have been described in the genes coding for the 4 β-voltage-gated sodium channel subunits. These mutations were found in patients with SCD phenotypes, such as BrS, sudden infant death syndrome (SIDS), sudden unexpected nocturnal death syndrome, and idiopathic ventricular fibrillation. The molecular mechanisms underlying the observed phenotypes were diverse, but the majority of these β-subunit mutations reduced the Na\textsubscript{v}1.5-mediated $I_{Na}$. We review here briefly the evidence demonstrating that mutations of the proteins of the Na\textsubscript{v}1.5 macromolecular complexes cause severe electric disturbances.

**α1-Syntrophin**

Na\textsubscript{v}1.5 is part of the dystrophin multiprotein complex; Gavillet et al demonstrated that Na\textsubscript{v}1.5 interacts with dystrophin via adaptor syntrophin proteins (see also Figure 2A). Similar to the binding with SAP97, this interaction is dependent on the last 3 residues (SIV) of the Na\textsubscript{v}1.5 protein. Two missense mutations in SNTA1, encoding α1-syntrophin, have been described in patients with congenital LQTS. The SNTA1 mutation, p.A390V, was reported to disrupt a

**Figure 1. Topography of Na\textsubscript{v}1.5 channel and its interacting proteins.** The proteins for which a binding site has been mapped are represented: 14-3-3 protein γ-isoform, calmodulin-dependent protein kinase II (CaMKII) δ-c, multicycop suppressor of gsp1 (MOG1), ankyrin-g, fibroblast growth factor like 13 (FGF13), calmodulin, Neural precursor cell Expressed, Developmentally Downregulated 4-2 (Nedd4-2)-like ubiquitin ligases, syntrophin proteins adapting either dystrophin or utrophin, protein tyrosine phosphatase-H1, synapse-associated protein 97. The proteins with question marks were found to interact with Na\textsubscript{v}1.5 but the sites of interaction are not yet known (CAR is coxsackie and adenovirus receptor and Desmog2-1 is desmoglein-2). Only 1 of the 4 β-subunits is represented (red). SIV indicates serine–isoleucine–valine.
macromolecular complex comprising neuronal nitric oxide synthase, plasma membrane Ca-ATPase type 4b, and Na\textsubscript{v}1.5 with syntrophin. The mutant syntrophin protein increased the late Na\textsuperscript{+} current, a finding that is consistent with the LQTS phenotype. Increased nitrosylation of Na\textsubscript{v}1.5, when the mutant syntrophin was coexpressed in HEK293 cells was observed. Further, the mutation SNTA1 p.A257G was found in 3 unrelated LQTS probands. Although no increase in the late \(I_{\text{Na}}\) was observed with this variant, significant increase in peak \(I_{\text{Na}}\) and slowed fast inactivation resulted from the co-expression of this mutant syntrophin. The gene SNTA1 was also found to be mutated in 8 cases of patients with SIDS and these variants caused an increase of the Na\textsubscript{v}1.5-mediated late \(I_{\text{Na}}\) which was inhibited by neuronal nitric oxide synthase inhibitors.

**Caveolin-3**

Caveolin proteins are important components of caveolae, which are cholesterol-rich plasma membrane invaginations where signaling molecules and ion channels are enriched. Caveolin-3 (Cav3) is encoded by the gene CAV3; it is the predominant caveolin isoform expressed in cardiac cells. CAV3 was found to be mutated in patients with congenital LQTS and SIDS. Cav3 was coimmunoprecipitated with Na\textsubscript{v}1.5 in rat cardiac tissue and HEK293 cells. Immunofluorescence stainings showed that the 2 proteins are colocalized at the

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**Figure 2.** A, Proximity ligation assay staining using antibodies for Na\textsubscript{v}1.5 and pan-syntrophin demonstrating the specific location of the interaction between these 2 proteins at the lateral membranes of mouse cardiac cells (red dots). In green, immunofluorescence staining demonstrating the presence of connexin43 at the intercalated disc (ID). B, Depending on the partner proteins, they interact with Na\textsubscript{v}1.5 is found either at the ID region, or at the lateral membrane (composed of crest regions and t-tubules) of cardiomyocytes. Along the crests, functional sodium channels do not distribute homogenously, but segregate in densely populated clusters, coexisting with areas devoid of functional channels. Reprinted from Shy et al\textsuperscript{25} with permission of the publisher. Copyright ©2014, Wolters Kluwer Health.

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**Figure 3.** Upper, Isolated mouse ventricular myocyte with double immunofluorescence staining (imaged with confocal microscopy). Na\textsubscript{v}1.5 (green) is expressed at the intercalated discs, lateral membrane. The punctate staining most likely represents the expression at the t-tubules. Syntrophin is only expressed at the lateral membrane where it colocalizes with Na\textsubscript{v}1.5 (see arrow in merge showing the yellow region of colocalization). Lower, Stainings of myocytes from genetically modified mice (truncation of the last 3 residues of Na\textsubscript{v}1.5 interacting with syntrophins and synapse-associated protein 97 [SAP97], ΔSIV) illustrating the reduction of Na\textsubscript{v}1.5 expression exclusively at the lateral membrane. Reprinted from Shy et al\textsuperscript{25} with permission of the publisher. Copyright ©2014, Wolters Kluwer Health. SIV indicates serine–isoleucine–valine.
lateral membrane of the cardiomyocytes. The coexpression of Na,1.5 and the LQTS and SIDS mutants of Cav3 in HEK293 cells were also shown to increase the late Na+ inward current. It has been proposed that both Cav3 and SNTA1 mutations share a common mechanism in releasing inhibition of neuronal nitric oxide synthase, leading to an increase in Na,1.5 S-nitrosylation and, as a result, augmented late I_{Na}.

Glycerol-3-Phosphate Dehydrogenase 1-Like Protein
Glycerol-3-phosphate dehydrogenase 1–like protein (GPD1L) is an enzyme homolog to GPD1, a key enzyme of the respiratory chain. In 2002, a locus on chromosome 3 in a family with BrS was detected, and later a missense mutation in the gene coding for GPD1L was observed. Coexpression experiments showed that mutant GPD1L reduced the Na,1.5-mediated I_{Na}. Three other GPD1L mutations have been described in babies that died of SIDS. Expression of these SIDS variants in neonatal mouse cardiomyocytes also decreased I_{Na}, demonstrating that patients with SIDS may have decreased I_{Na} similarly to BrS. The mechanisms by which the mutations of GPD1L reduce the I_{Na} have been investigated in expression systems. It is proposed that Ser1503 of Na,1.5 is phosphorylated by protein kinase C (PKC) and that this reduces the I_{Na}. It has been shown that the activity of PKC depends on GPD1L function, and that the mutant GPD1L variants lead to a further decrease in the I_{Na} after a diacylglycerol-dependent stimulation of PKC. Another possible mechanism is that the GPD1L mutant increases nicotinamide adenine dinucleotide phosphate and via PKC effects on mitochondria, and this decreases reactive oxygen species, which then reduce the I_{Na} by yet unknown mechanisms.

MOG1
Multicopy suppressor of gsp1 (MOG1) is a 29-kd protein encoded by the RANGRF gene. MOG1 interacts with the intracellular loop of Na,1.5 between domains II and III. The 2 proteins also colocalize at the IDs in mouse ventricular cells. MOG1 coexpression in HEK293 cells increased the Na,1.5-mediated current without altering its biophysical properties, suggesting that MOG1 is a cofactor for optimal channel expression at the cell membrane. A human study described 1 BrS variant of MOG1 that reduced the expression of Na,1.5 at the cell membrane of rat atrial cardiomyocytes and decreased the I_{Na}. The details about how MOG1 regulates the expression of Na,1.5 are still to be investigated.

Plakophilin-2
Plakophilin-2 (PKP2) is found at the IDs of cardiomyocytes. Delmar’s group demonstrated that Na,1.5 interacts not only with PKP2 at the IDs, but also in a complex with ankyrin-G and connexin43. Whether the interactions between these different proteins of the IDs are direct or indirect and the site of interaction with Na,1.5 remain to be determined. In a recent study with 200 BrS patients, 5 missense mutations in the gene PKP2 were demonstrated. The I_{Na} and the density of Na,1.5 channels at the ID were reduced when PKP2 mutant proteins were coexpressed. This experimental evidence strongly supports a role for PKP2 in targeting and regulating the density of Na,1.5 at the IDs and also its implication in BrS.

Fibroblast Growth Factor Homologous Factors
Fibroblast growth factor homologous factors (FGFs) are cytosolic proteins that can modulate both cardiac Na+ and Ca2+ channels. The proximal part of the C-terminal domain of Na,1.5 has been shown to bind to murine FGFI3 and human FGFI2 (Figure 1). Knockdown of FGFI3 in murine ventricular myocytes decreased I_{Na} and channel availability. Interestingly, a genetic variant of the gene coding for human FGFI2 (p.Q7R) was identified in 1 BrS patient. When expressed in rat myocytes, this variant reduced I_{Na} and channel availability, hence leading to a loss of function which is consistent with the BrS phenotype.

Synapse-Associated Protein 97
SAP97 regulates the targeting, localization, and function of cardiac K+ and sodium channels via their PDZ domain–binding motifs located in the C termini. The interaction between SAP97 and Na,1.5 has been demonstrated independently by the Abriel and the Jalife laboratories. Although there is strong experimental evidence for a direct interaction between these 2 proteins via the Na,1.5-SIV motif and a SAP97 PDZ domain, the exact role of SAP97 on the regulation of Na,1.5 function remains to be clarified. A mutation found in 1 patient with BrS modified the valine of the SIV motif of Na,1.5 into a methionine. This mutation was shown to specifically reduce the interaction with SAP97, but not α1-syntrophin. In parallel, the mutation decreased the number of Na,1.5 channels and I_{Na}. It seems likely that genetic variants in DLG1, the gene coding for SAP97, will be found in patients with inherited channelopathies associated with SCD.

Calcium Channel Macromolecular Complexes
The voltage-gated L-type calcium channel, Ca,1.2, is the main pathway for the entry of calcium into cardiac cells. The pore-forming Ca,α,2 subunit carries the main biophysical and pharmacological properties of the channel that plays a key role in excitation–contraction coupling and AP duration. The Ca,α,2 subunit is modulated by interactions with different accessory subunits (Figure 4). It is associated with 4 different β-isofoms (Ca,β1–4) and 4 different α,δ-isofoms (Ca,α,δ1–4). Both Ca,β and Ca,α,δ have been shown to play dual roles in regulating both the biophysical properties and trafficking of Ca,α,2 channels. In addition to these regulatory subunits, the γ subunits (8 isoforms) have been described as a third class of accessory subunits. In cardiomyocytes, the fully functional Ca,1,2 channel, which is composed of at least Ca,α,2, Ca,β, and Ca,α,δ subunits (Figure 4) can be considered as the main core macromolecular calcium channel complex.

Ca,1,2 Interacting Proteins
All 4 Ca,βs increase the Ca2+ current when they are coexpressed in heterologous expression systems along with a Ca,α,2 subunit. Ca,βs also alter the voltage dependence and kinetics of activation and inactivation. Furthermore, Ca,β subunits either regulate or are needed for the modulation of Ca,α, by protein kinases, G proteins, ubiquitin ligases of the Neural precursor cell Expressed, Developmentally Downregulated 4 family, and small RGK (Rem, Rem2, Rad, and Gem/Kir) proteins (Figure 4). Ca,β proteins have also been shown to
interact with Ahnak1, a protein involved in the protein kinase A (PKA)-mediated control of the CaV1.2 channel. Altogether, these data demonstrate that CaVβ subunits play a pivotal role in the localization and regulation of cardiac calcium channels.

The CaVα1-δ auxiliary subunits are the product of a single gene that is post-translationally cleaved into α2 and δ peptides and remain associated via disulfide bonds. Only CaVα1-δ1 and CaVα1-δ2 proteins have been found to be expressed in mouse heart. Coexpression of the CaVα1-δ subunit, along with CaVα1 and CaVβ subunits, accelerated activation and deactivation kinetics and significantly increased I_{Ca}. Animals lacking the CaVα1-δ1 subunit demonstrated reduced basal myocardial contractility and relaxation and decreased L-type Ca^2+ peak current amplitude. CaVα1-δ1 has been recently shown to be essential in the regulation of the CaV1.2 channel cell surface density mediated by the deubiquitylase USP2-45.

The CaVγ proteins consist of 4 transmembrane domains with intracellular N- and C-terminal ends. In the human heart, only CaVγ4, 6, 7, and 8 have been found to be expressed. The CaVγ subunits differentially modulate calcium channel function when coexpressed with the CaVβ1b and CaVα1-δ1 subunits, altering both activation and inactivation properties.

The effects of CaVγ on CaV1.2 function are dependent on the subtype of CaVβ subunit. In cardiac myocytes, CaV1.2 channels are mainly localized in the t-tubular system (Figure 5). L-type calcium channels are 3- to 9-fold enriched in the t-tubule membrane than on the extratubular surface sarcolemma. Within the t-tubule, studies have estimated that ≈75% of the L-type calcium channels are localized in the dyad domains (Figure 5), thus constituting the main CaV1.2 macromolecular complex in cardiac cells. The dyad represents a small area where CaV1.2 channels, situated on the cytoplasmic side of the plasma membrane, are in opposition to the ryanodine receptor type 2 that is situated on the membrane of the sarcoplasmic reticulum. An essential component of the dyadic cleft is junctophilin 2 (Figure 5). Junctophilin 2 is a cleft protein that anchors the t-tubular membrane to the sarcoplasmic reticulum membrane; doing so it plays a key role in maintenance and function of that space. In junctophilin 2 knockout mice, reduction in the number of dyads was observed, suggesting that junctophilin 2 is responsible for maintaining the dyadic structure. A calcium-binding...
protein, sorcin, expressed in cardiac cells, has also been shown to interact with both Ca\textsubscript{1.2} and ryanodine receptor type 2.\textsuperscript{64} Finally, PKA and Ca\textsuperscript{2+}/calmodulin-dependent protein kinase II (CaMKII), which are known to mediate the regulation of Ca\textsubscript{1.2} channel activity via their interactions with the C-terminal of the Ca\textsubscript{\alpha\textsubscript{1C}} subunit, have also been shown to be part of the dyad.\textsuperscript{65}

Recently, other partner proteins have been described to be important in regulating Ca\textsubscript{1.2} expression at the t-tubule. Amphiphysin 2, also called bridging integrator 1, belongs to the BAR domain proteins superfamily and is involved in membrane invagination.\textsuperscript{66} Hong et al\textsuperscript{66} have shown that bridging integrator 1 is expressed at the t-tubules, initiates t-tubuleogenesis, and delivers CaV1.2 to t-tubules.\textsuperscript{66} Ahnak1 is indirectly associated with the L-type Ca\textsuperscript{2+} channel via its \(\beta_2\)-subunit and has been shown to be located at the sarcolemma and t-tubules of cardiomyocytes.\textsuperscript{66} Similar to bridging integrator 1, the exact localization within the t-tubule system is not known. Nevertheless, its implication in the regulation of \(I_{\text{Ca}}\) via the \(\beta\)-adrenergic pathway suggests the presence of Ahnak1 and Ca\textsubscript{1.2} channels in extradyadic complexes. Dysferlin, a member of the ferlin family, has recently been shown to be expressed mainly at the ID of cardiomyocytes and is also present at the t-tubules.\textsuperscript{67} These observations suggest that other Ca\textsubscript{1.2} macromolecular complexes, which may be Cav3-dependent, also exist in the extradyadic compartment (Figure 5). Recently, a subpopulation of Ca\textsubscript{1.2} channels that is located in the caveolae has been found to be part of a macromolecular signaling complex, including \(\beta_2\)-adrenergic receptor, adenylate cyclase, protein phosphatase 2A, and PKA.\textsuperscript{68} Calcineurin, another interacting/regulating protein of Ca\textsubscript{1.2} channels, has also been shown to be present in caveolae and the t-tubule system.\textsuperscript{69} Via its association with the adapter protein A kinase–anchoring protein (AKAP5), calcineurin interacts with Cav3.\textsuperscript{70} Altogether, these findings suggest the presence of t-tubular distinct Ca\textsubscript{\alpha\textsubscript{1.2}} macromolecular complexes that are also present in extradyadic compartments (Figure 5).

In parallel, other groups have demonstrated that a subpopulation of Ca\textsubscript{1.2} channels is localized to caveolae in the extra T-tubular lateral membrane of ventricular cardiomyocytes (Figure 5), thus suggesting that at least a third Ca\textsubscript{1.2} macromolecular complex exists.\textsuperscript{68}

**Mutations in Genes Coding for Calcium Channel–Interacting Proteins and Associated Disorders**

Mutations in genes coding for calcium channel accessory subunits have been linked to BrS and short-QT syndrome type 6.\textsuperscript{71,72} A loss-of-function mutation (p.S481L) of the \(\text{CACN}B2\) gene, encoding the Ca\textsubscript{\beta2} subunit, was found in a BrS patient.\textsuperscript{71} Despite the large \(I_{\text{Ca}}\) mutation-induced decrease in heterologous expression systems, no reduction of Ca\textsubscript{1.2} channel number has been observed at the plasma membrane. This suggests another mechanism of Cav regulation than the traffic defect that is generally observed in BrS. Templin et al\textsuperscript{73} reported a mutation (p.S755T) in \(\text{CACN}A2D1\), the gene encoding the Ca\textsubscript{\alpha\textsubscript{1C}}-\text{81} subunit, in a SCD patient with short-QT syndrome. An important decrease of the \(I_{\text{Ca}}\) was observed with the expression of the mutant variant without any modification of the protein expression, thus suggesting that the single channel biophysical properties of the L-type channel were altered.

The p.I5236T mutation of Ahnak1, identified in patients with hypertrophic cardiomyopathy,\textsuperscript{73} increased the \(I_{\text{Ca}}\) as well as shifted slightly leftward its voltage dependence,\textsuperscript{73} similar to what has been observed after PKA activation. It is proposed that Ahnak1 may be an important target of PKA-mediated phosphorylation in the enhancement of L-type \(I_{\text{Ca}}\) by the \(\beta\)-adrenergic receptor type 2. Furthermore, 3 other Ahnak1 variants were identified in hypertrophic and dilated cardiomyopathy patients.\textsuperscript{74} Contrary to what has been proposed in the former study, it was recently found that Ahnak1 is not essential for \(\beta\)-adrenergic upregulation of \(I_{\text{Ca}}\) in mice. Instead, Ahnak1 interacts with the Ca\textsubscript{\alpha\beta} subunit to modulate the \(\beta\)-adrenergic response of \(I_{\text{Ca}}\).\textsuperscript{74}

**Potassium Channel Macromolecular Complexes and Associated Disorders**

Cardiac potassium channel proteins are coded by >40 different genes.\textsuperscript{75} In addition, several auxiliary subunits and associated proteins are involved in the trafficking, distribution, and anchoring of potassium channels at specific microdomains at the plasma membrane, and contribute to their organization in macromolecular complexes.\textsuperscript{76} Such partners help in the control of potassium channel expression and biophysical properties, thus regulating the plasticity of cardiac electric activity both under normal conditions and in disease states. In this section, we review the interactions of the major potassium channels as part of macromolecular assemblies and the role of such assemblies in cardiac excitation and repolarization.

**The Strong Inward-Rectifying Potassium Channels**

Among the 3 strong inward-rectifying potassium channels (Kir2.1, 2.2, and 2.3) that express in the heart, Kir2.1 is the most abundant in the ventricles. Kir channels are responsible for inward rectifier potassium current (\(I_{\text{Kir1}}\)) and are involved in the depolarization, repolarization, and resting phases of the cardiac AP.\textsuperscript{77} Kir subunits assemble to form tetrmeric channels in many cell types, including cardiac myocytes.\textsuperscript{78,79} \(I_{\text{Kir1}}\) contributes significant repolarizing current between −30 and −80 mV, and thus is responsible for the terminal phase of the AP.\textsuperscript{80} In addition, it serves as the primary conductance control of the resting membrane potential in ventricular myocytes.\textsuperscript{81} These channels show strong rectification between −50 and 0 mV, which means that they remain closed during the AP plateau; they only open when the membrane potential repolarizes to levels between −30 and −80 mV, which in the normal AP occurs during the late phases of the AP. Rectification is achieved by a voltage-dependent blockade by intracellular magnesium and polyamines, such as putrescine, spermine, and spermidine,\textsuperscript{82} which interact with at least 3 amino acid residues located inside the pore of the channel.\textsuperscript{83}

Loss-of-function mutations of Kir2.1 have been identified in patients affected by Andersen–Tawil syndrome, which is also referred to as LQTS type 7 and is characterized by delayed repolarization.\textsuperscript{84} Because in addition to the heart Kir2.1 is also expressed in other organs, such as skeletal muscle, Andersen–Tawil syndrome is associated with hypokalemic
periodic paralysis and skeletal developmental abnormalities. In the heart, reduction of $I_{K1}$ leads to QT prolongation and predisposes to arrhythmias; yet QT prolongation is less prominent in patients presenting Andersen–Tawil syndrome than in other types of LQTS. Moreover, although Andersen–Tawil syndrome patients do develop ventricular tachyarrhythmias, including torsades de pointes, SCD is rare in these patients.

Only 3 cases of Kir2.1 gain-of-function mutation have been reported. In 2005, Xia et al. reported on a Kir2.1 gain-of-function mutation (V93I) in a large Chinese family with atrial fibrillation. Subsequently, 2 different gain-of-function mutations (D172N and E299V) in the KCNJ2 gene were reported in patients with short-QT syndrome type 3. Increased $I_{K1}$ shortens repolarization and the QT interval and exerts a proarrhythmic effect both in the atria and the ventricles.

**Kir2 Channels Have Multiple Functional Partners**

In 2001, Leonoudakis et al. identified a direct association of Kir2.1, Kir2.2, and Kir2.3 with SAP97. They further demonstrated that a complex composed of members of the membrane-associated guanylate kinase protein family (SAP97, Cav3, α- and β-syntrophin, dystrophin, and dystrobrevin, all members of the dystrophin-associated protein complex, as well as SAP97, Veli-1, and Mint1) associates with Kir2 channels via the C-terminal PDZ-binding motif. Also using in vitro protein interaction assays they showed that SAP97, Veli-1, or Veli-3 binds directly to the Kir2.2 C terminus and recruits CASK and proposed a model whereby Kir2.2 associates with distinct SAP97–CASK–Veli–Mint1 complexes. Subsequently, using immunoaffinity purification and affinity chromatography from skeletal and cardiac muscle and brain, they discovered that α-1-, β-1-, and β-2-syntrophin, dystrophin, and dystrobrevin, all members of the dystrophin-associated protein complex, also interact with Kir2.x channels. In this regard, cardiomyocytes from the dystrophin-deficient mdx mouse show a small but significant decrease in Kir2.1 protein. It is also possible that dystrophin-related proteins contribute to determining the subcellular localization of Kir2.x channels in cardiomyocytes, similar to what has been demonstrated for Na$_\text{v}$.1.5 channels. As demonstrated by affinity pull-down experiments, Kir2.1 to 3 and Kir4.1, all bind to scaffolding proteins but with different affinities for the dystrophin-associated protein complex, as well as SAP97, CASK, and Veli.

In 2001, Dart and Leyland showed that Kir2.1 associates with AKAP5, which is a multivalent-anchoring protein that binds PKA, PKC, and calcineurin. AKAP5 is targeted to the intracellular N- and C-terminal domains of Kir2.1 to anchor kinases close to key channel phosphorylation sites and is required for appropriate modulation of channel function. More recently, it was suggested that both Kir2.1 and AKAP are part of a macromolecular signaling complex that includes the β1-adrenergic receptor and SAP97. Kir2.1 may also associate with Cav3 in human cardiac cells. Cav3 mutations have been shown to reduce cell surface expression of Kir2.1 with consequent reduction of $I_{K1}$ density. Such an effect may add to the previously described late $I_{K1}$ increase and contribute to delayed repolarization and arrhythmia generation in Cav3-mediated LQT9. Filamin-A increases the number of functional Kir2.1 channels on membrane in arterial smooth muscle cells. It seems to act as a cytoskeletal anchoring protein for the Kir2.1 channel, stabilizing its surface expression. However, although filamin has been shown to localize at the Z lines in cardiomyocytes, it is unknown whether pools of Kir2.x channels colocalize with filamin-A. Finally, it has been demonstrated that Kir2.1 interacts with the API1 adaptin complex through an unusual Golgi exit signal dictated by a tertiary structure, localized within the confluence of the Kir2.1 cytoplasmic NH3 and COOH terminal domains. The signal allows properly folded Kir2.1 channels to insert into clathrin-coated vesicles at the trans-Golgi for export to the cell surface, which is a critical regulatory step for controlling trafficking and cell surface expression of the Kir2.x channels.

**Kir2.1 and the Na$_{\text{v}}$.1.5/Kir2.1 Channelosome**

There is a strong relationship between the inward $I_{Na}$ and the $I_{K1}$, the 2 most important ionic currents controlling ventricular excitability: by controlling the resting membrane potential, $I_{K1}$ modifies Na$^+$ channel availability and, therefore, cell excitability. In addition, $I_{K1}$–$I_{Na}$ interactions are important in stabilizing and controlling the frequency of the electric rotors that are responsible for the most dangerous cardiac arrhythmias, including ventricular tachycardia and ventricular fibrillation. Recent data demonstrated that the $I_{Na}$–$I_{K1}$ interplay involves a reciprocal modulation of expression of their respective channel proteins (Kir2.1 and Na$_{\text{v}}$.1.5) forming a channelosome within a macromolecular complex (Figure 6). Furthermore, evidence suggests that conditions that result in Na$_{\text{v}}$.1.5 protein reduction, such as it occurs in the dystrophin-deficient mdx$^{\text{c5}}$ mice, are accompanied by a concomitant reduction in Kir2.1 protein levels. Importantly, the finding that coexpression of Na$_{\text{v}}$.1.5 may reduce internalization of Kir2.1 was a central mechanistic observation, with important implications in the control of cardiac excitability and SCD.

Recently, Gillet et al. investigated in vivo the interactions of SAP97 with Kir2.1 and Na$_{\text{v}}$.1.5 by generating a genetically modified mouse model in which SAP97 expression was constitutively suppressed in cardiomyocytes. As expected, $I_{K1}$ was reduced in the SAP97 knockout mice (Figure 7). Unexpectedly, $I_{Na}$ and Na$_{\text{v}}$.1.5 localization at the ID were unaffected by the loss of SAP97 expression. Ostensibly, the data presented by the papers of Gillet et al. and of Shy et al. about Na$_{\text{v}}$.1.5 seem to contradict previous work. Yet there are substantial differences between the 2 mouse models and the previous studies that need to be considered. Most important in both mouse models, genetic modification is present early in development, whereas in the other studies, SAP97 expression was silenced in adult myocytes that were kept in culture. Therefore, it is conceivable that the consequences on $I_{Na}$ could be different in an inducible SAP97 knockout mouse model. However, Na$_{\text{v}}$.1.5 is known to interact with other regulatory proteins at the IDs, such as connexin43, PKP2, and ankyrin-G. Furthermore, recent studies suggest that there are microdomains of Na$_{\text{v}}$.1.5 at the IDs. In particular, a population of Na$_{\text{v}}$.1.5 is located at the periphery of gap junctions in a so-called perinexus...
region that has been proposed to be involved in ephaptic conduction. It might be possible that constitutive deletion of SAP97 led to compensatory modifications in the expression and organization of 1 more partner proteins that contributed to maintain NaV1.5 expression.

The KATP Channel Macromolecular Complex

ATP-sensitive K⁺ (KATP) channels function as metabolic sensors in many cell types. They are octameric assemblies of a sulfonylurea receptor (SUR) and an ion-conducting subunit (Kir6.x). This enables them to directly couple their energy metabolism to cellular excitability and function as a crucial regulatory mechanism in the cell response to metabolic demand. Genetic manipulation of cardiac KATP subunits has revealed a role of these channels in arrhythmia generation. Human KATP mutations underlie different KATP channelopathies and can substantially increase the risk of heart disease.

The pore-forming subunit of the KATP channel is 1 of 2 members of the inwardly rectifying family of K⁺ channels, Kir6.1 and Kir6.2 coded by KCNJ11 and KCNJ8, respectively. The 2 SUR subunits (SUR1 and SUR2) are respectively coded by ABCC8 and ABCC9. Although several SUR splice variants have been described, the most commonly studied are SUR1, SUR2A, and SUR2B. Like other Kir channels, Kir6.x subunits have a cytoplasmic N and C terminus with 2 transmembrane domains and a pore-forming H5 loop. SUR has multiple transmembrane domains with 2 large intracytoplasmic loops, the first and second nucleotide-binding domains (NBD1 and NBD2), which contain consensus sequences for the hydrolysis of nucleotides (Walker A and B motifs).

Coexpression of the 2 types of subunit is necessary to achieve functional expression of KATP channels and the assembly of a specific Kir6.x with a specific SUR generates currents with a particular single-channel conductance, nucleotide regulation, and pharmacology. However, accumulating evidence suggests that the KATP channel protein complex is part of a multisubunit macromolecular complex that may also include additional metabolically active protein subunits, including adenylate kinase, creatine kinase, and lactate dehydrogenase. In addition, it has been demonstrated that 14-3-3 proteins promote the cell-surface expression of heterologously expressed and native KATP channels by functionally antagonizing the arginine-based endoplasmic reticulum localization signal that many ion channels and proteins require to reach the cell surface, and that is present in SUR1. Recently it was shown that KATP channels are stalled in the Golgi complex of ventricular, but not atrial, cardiomyocytes. It was also demonstrated that PKA-dependent phosphorylation of the C terminus of Kir6.2 by sustained β-adrenergic stimulation leads SUR1-containing channels to reach the plasma membrane of ventricular cells by silencing the arginine-based retrieval signal. Therefore, it was suggested that sympathetic nervous stimulation might enable adaptation to metabolic challenges by releasing KATP channels from storage in the Golgi.

In a recent proteomics study, glycolytic enzymes previously described for the KATP channel complex were shown to coimmunoprecipitate with KATP channel subunit from heart, endothelium, and pancreas, suggesting that glycolytic ATP
production contributes to fine tuning of K<sub>ATP</sub> channel opening in these tissues.

Physical interaction between cardiac K<sub>ATP</sub> channels and the Na<sup>+</sup>/K<sup>+</sup> ATPase has also been suggested, which might provide mechanistic insight into their functional interaction with regards to possibly sharing or competing for the same local pool of submembrane ATP/ADP. Physical interaction between cardiac K<sub>ATP</sub> channels and the Na<sup>+</sup>/K<sup>+</sup> ATPase has also been suggested, which might provide mechanistic insight into their functional interaction with regards to possibly sharing or competing for the same local pool of submembrane ATP/ADP. Finally, Kir6.2 and SUR2A are expressed at a higher density at the IDs in mouse and rat hearts, where they colocalized with PKP2 and plakoglobin. The disruption of the desmosomal complex in PKP2-deficient mice results in downregulation of KATP channels, suggesting a possible role of these channels in cell-to-cell communication.

**Diversity of Voltage-Gated Potassium Channels**

Voltage-gated potassium (K<sub>V</sub>) channels are members of the Shal subfamily of voltage-gated K<sup>+</sup> channel pore-forming α-subunits. K<sub>V</sub> channels are formed by assemblies of 4 α-subunits plus accessory subunits. They function to control resting membrane potentials, shape AP characteristics and influence the responses to neurotransmitters and neurohormones. There are extensive differences in their kinetics of activation and inactivation among the various K<sub>V</sub> channels, and specific channels underlie specific currents in the heart. For example, K<sub>V</sub>4.x channels, including K<sub>V</sub>1.4, K<sub>V</sub>4.2, and K<sub>V</sub>4.3, coded by KCNA4, KCND2, and KCND3, respectively, activate and inactivate rapidly and underlie the transient outward current (I<sub>to</sub>). K<sub>V</sub>1.5, which is coded by KCNA5 and forms the atria-specific ultrarapid delayed rectifier K<sup>+</sup> current (I<sub>Kur</sub>), inactivates much more slowly. K<sub>V</sub>7.1 is coded by KCNH2, the human ether-a-go-go-related gene (hERG). In contrast to K<sub>V</sub>4.1 to 3, hERG activates and inactivates rapidly, then conducts most of its current during its recovery from inactivation. K<sub>V</sub>2.1, coded by KCNB1, is a slow delayed rectifier K<sup>+</sup> channel that underlies I<sub>k,slow</sub> in rat cardiomyocytes. Targeted elimination of K<sub>V</sub>2 channels in mouse ventricular myocytes leads to prolongation of the action potential duration and the QT interval. K<sub>V</sub>2.1 may have distinct physiological roles in atrial and ventricular myocytes. Finally, I<sub>Ks</sub>, the α-subunit (KCNQ1) of the slowly activating delayed rectifier K<sup>+</sup> current activates and deactivates slowly.

**Functional Interactions of K<sub>V</sub> Channels in their Microenvironment**

In the heart, K<sub>V</sub>4.2, K<sub>V</sub>4.3, and K<sub>V</sub>1.4 may assemble to generate transient outward currents. K<sub>V</sub>4.3/K<sub>V</sub>4.2 subunits form the rapidly recovering I<sub>to</sub> channels, whereas K<sub>V</sub>1.4 forms the slowly recovering I<sub>k,slow</sub> channel, both of which underlie the early phase of AP repolarization and contribute to the AP plateau. Both channel types are differentially expressed in the ventricles, contributing to regional heterogeneities in AP shape and duration.

Substantial evidence indicates that these channels function as integral components of macromolecular protein complexes, and that expressed K<sub>V</sub> channels can be regulated...
by post-translational modifications, including phosphorylation. Also coexpression with accessory or regulatory proteins in heterologous expression systems modifies cell surface expression, subcellular distribution, channel stability, and biophysical properties of KV4 channels. Hence, the specific-expression, subcellular distribution, channel stability, and proteins in heterologous expression systems modifies cell surface that have a mass of \( \approx 40 \) kDa. Nine KV\( \beta \) subunits are encoded by 4 genes. They have been shown to associate with KV\( \alpha \)-subunits. The KV\( \beta \)\( 1, \beta \)\( 2, \) and KV\( \beta \)\( 3 \) proteins, which are coded by different genes, are the only KV\( \beta \) proteins expressed in the mammalian heart. Additional variability is produced by alternative splicing on the N-terminal region. KV\( \beta \) subunits are localized in the cytosol with a conserved carboxyl terminal and a variable amino terminal; they form a tetrameric structure and are associated in a 1:1 ratio with the KV\( \alpha \)-subunit. KV\( \beta \)\( 1 \) and KV\( \beta \)\( 3 \) associate with KV\( \alpha \)-subunits early during their biosynthesis in the endoplasmic reticulum and exert a chaperone-like effect enabling their stable expression at the plasma membrane. Notably, this chaperone-like property of KV\( \beta \) subunit does not apply to all KV\( \alpha \) channels. The most important effect of KV\( \beta \)\( 1 \) on the voltage-dependent outward current is to accelerate its rate of inactivation, an effect that is mediated through a ball-and-chain like process whereby the KV\( \alpha \)-N-terminal domain blocks the inner cavity of the KV\( \alpha \)-subunit pore. In addition, by binding to the C terminus of the KV channel, KV\( \beta \) can accelerate the C-type inactivation. In heterologous expression systems, coexpression of KV\( \beta \)\( 1.3 \) with KV\( \alpha \)\( 1.5 \) is necessary for the cyclic adenosine 3',5' monophosphate (cAMP)-dependent PKA-mediated increase in KV current. Moreover, consistent with the presence of multiple phosphorylation sites on the \( \alpha \) and \( \beta \)-subunits, PKC reduces the KV current of KV\( \alpha \)\( 1.5 \) channels only when coexpressed with KV\( \beta \)\( 1.2 \), which may provide an explanation for the effects of the \( \beta \)-adrenergic or PKC stimulation on KV in human atrial myocytes. The duration and the frequency of membrane depolarization can significantly modify the rate of inactivation of KV in human atrial myocytes. This effect is modulated by the activation of CaMII and may also involve the interaction between KV\( \alpha \)\( \beta \) and the KV\( \alpha \)\( \alpha 1.5 \) subunits. The contribution of KV to the abbreviation of the AP duration during atrial fibrillation and the fact that the KV\( \alpha \)\( 1.5 \) channel is more abundantly expressed in atrial than ventricular myocardium are additional examples of the important role played by KV\( \beta \) subunits in cardiac pathophysiology. Finally, KV\( \beta \) subunits have been shown to confer sensitivity to redox modulation and hypoxia to KV\( \alpha \)\( 4.2 \) channels.

Other Ancillary Subunits of KV channels

The best-known partner of KV\( \alpha \) channels is the cytoplasmic KV channel–interacting protein, KChIP2, which has been shown directly to be an essential component of KV\( \alpha \) channels in myocardium. The KChIPs were first identified in brain using the KV\( \alpha \)\( 4 \) N terminus as bait in a yeast 2-hybrid screen. They were shown to have 4 EF (EF hand calcium binding motif)-hand-like domains and bind calcium ions. The expression of KChIP and KV\( \alpha \) together reconstitutes several features of native A-type currents by modulating the density, inactivation kinetics, and rate of recovery from inactivation of KV\( \alpha \) channels in heterologous cells. All 3 KChIPs were shown to co-localize and coimmunoprecipitate with brain KV\( \alpha \)\( \alpha \)-subunits, and therefore to be integral components of native KV\( \alpha \) channel complexes. KChIP2 assemblies with the N terminus of the pore-forming KV\( \alpha \)\( \alpha \)-subunit and acts as a chaperone to regulate both surface expression and electrophysiological properties of the channel. In heart, KChIP2 coimmunoprecipitates with KV\( \alpha \)-subunits of KV\( \alpha \)\( 4.2 \) and KV\( \alpha \)\( 4.3 \) from adult mouse ventricles, and the targeted deletion of the mouse KChIP2 locus (Kcnip2) abolishes ventricular \( I_{\text{tof}} \). In addition, KChIP2 protein expression is highly reduced in the ventricles of homozygous KV\( \alpha \)\( 4.2 \) knockouts mice, suggesting that KV\( \alpha \) and KChIP2 proteins reciprocally regulate each other’s expression. In mouse ventricles, the KChIP2 mRNA level is somewhat larger in the epicardium than the endocardium. In contrast, large transmural gradients in KChIP2 expression together with large \( I_{\text{tof}} \) density gradients have been demonstrated across the human and the dog ventricular walls.

Dipeptidyl peptidase–like protein 6 is a protein that regulates the activation and inactivation properties of cardiac KV\( \alpha \) channels. Dipeptidyl peptidase–like protein 6 increases heterologously expressed KV\( \alpha \)\( 4 \) \( \beta \)-subunits at the cell surface, shifts the voltage dependences of activation and inactivation currents to more negative potentials, and accelerates the rates of current activation, inactivation, and recovery. Notably, when dipeptidyl peptidase–like protein 6 is coexpressed with KV\( \alpha \)\( 4.3 \) and KChIP2, it yields KV\( \alpha \) currents that closely resemble native cardiac \( I_{\text{tof}} \).

Transient outward K\( ^+ \) currents can be modulated by protein kinases. The nonreceptor protein tyrosine kinase c-Src is a member of a family of 9 closely related membrane-bound kinases defined by a common structure with a catalytic kinase domain and amino-terminal regulatory regions termed Src homology 2 (SH2) and 3 (SH3) domains. These modular domains mediate intramolecular and intermolecular interactions that are important in signal transduction. The KV\( \alpha \)\( 4.3 \) sequence contains SH2 and SH3 domain-binding motifs, making KV\( \alpha \)\( 4.3 \) a strong candidate for direct interaction with and phosphorylation by c-Src. Gomes et al have shown through glutathione S-transferase pull-down assays and coimmunoprecipitation, that KV\( \alpha \)\( 4.3 \) protein associates with c-Src and that the SH2 and SH3 domains of the kinase mediate this interaction, which may result in enhanced efficiency of KV\( \alpha \)\( 4.3 \) phosphorylation by c-Src leading to rapid modulation of KV\( \alpha \)\( 4.3 \) channel activity. SAP97 and KV\( \alpha \)\( 1.5 \) subunits can interact, directly or indirectly, both in the heart and in heterologous systems. Adenoviral overexpression of SAP97 in neonatal rat atrial myocytes leads to clustering of endogenous KV\( \alpha \)\( 1.5 \) subunits at myocyte–myocyte contacts and an increase in both \( I_{\text{tof}} \) and the number of 4-aminopyridine–sensitive potassium channels in...
cell-attached membrane patches. However, pull-down and coimmunoprecipitation assays in cardiac myocytes showed that the K, 4 channel C terminus, SAP97, and CaMKII interact together, and that the interaction is suppressed by SAP97 silencing and enhanced by SAP97 overexpression. In HEK293 cells, SAP97 silencing reproduced the effects of CaMKII inhibition on current kinetics and suppressed K, 4/ CaMKII interactions. Altogether, the above data suggest that SAP97 is a major partner for surface expression and CaMKII-dependent regulation of cardiac K, 4 channels.

As reviewed comprehensively elsewhere, KCNE genes encode a family of single transmembrane domain proteins called minK-related peptides (MiRPs) that function as accessory β-subunits of K, channels. When coexpressed in heterologous systems, MiRPs confer changes in K, channel conductance, gating kinetics, and pharmacology. Coexpression of K, 4 and K, 4-KChIP2 channels with MiRP1 affects the kinetics and the voltage-dependent properties and recapitulates the overshoot in peak current amplitude during current recovery, that is evident in human epicardial I, s. Inherited mutations in KCNE genes are associated with diseases of cardiac and skeletal muscle and the inner ear. For example, aspartate to asparagine substitution to p.D76N-MinK is linked to cardiac arrhythmia and deafness. Mutation of arginine to histidine (p.R83H) in MiRP2 is associated with periodic paralysis. Finally, targeted deletion of KCNE3, which encodes MiRP1, reduced (≈25%) ventricular I, s, densities by 25% with negligible changes in total or surface K, 4.2 expression.

The KCNE1 gene encodes a 129 amino acid protein in mouse and human that modifies the currents generated by hERG or K, LQT1. The delayed rectifier K+ currents resulting from expression of K, LQT1 alone are small and activate rapidly, but I, is reconstituted when minK is coexpressed with K, LQT1. Evidence suggests that KCNE1 may have preferential expression in the conduction system. Mutations in KCNE1 have been reported to cause LQTS.

MiRP2 is a member of the MinK-related peptide family that is coded by KCNE3. It coimmunoprecipitates with K, 4.3 from human atria. Interestingly, a missense mutation (p.R99H) in KCNE3 was identified in a family with BrS. Transfection of MiRP2 (with and without KChIP) decreases K, 4.3 current densities in heterologous expression systems. In addition, coexpression of the p.R99H MiRP2 mutant reversed the inhibitory effects of wild-type MiRP2 on K, 4.3 currents. Altogether, the above data suggest that MiRP2 is required for normal functioning of human I, s, channels and that gain-of-function mutations in MiRP2 predispose to BrS through augmentation of I, s. The KCNQ1 gene, encodes the K, 7.1 channel protein, which can form heteromultimers with 2 other potassium channel proteins, KCNE1 and KCNE3. In the human heart, the KCNQ1 gene encodes the pore-forming α-subunit, and KCNE1 (also known as minK) encodes the regulatory β-subunit of the KCNQ1–KCNE1 complex responsible for I, Ks, the slowly activating delayed rectifier K+ repolarizing current. Mutations in KCNQ1 are associated with hereditary LQTS1 (also known as Romano–Ward syndrome), Jervell and Lange-Nielsen syndrome, and familial atrial fibrillation. In 2002, Marx et al showed that modulation of L, αβ-adrenergic receptor stimulation requires targeting of cAMP-dependent PKA and protein phosphatase 1 to hKCNQ1 through the AKAP-9, also known as yotiao. These authors elegantly demonstrated that yotiao binds to the human KCNQ1 by a leucine zipper motif, which is disrupted by an LQTS mutation (hKCNQ1-G589D). Identification of the hKCNQ1 macromolecular complex reveals a mechanism for sympathetic nervous system modulation of cardiac action potential duration (APD) through L, 3. These data provided compelling evidence that the cardiac I, Ks, potassium channel is a macromolecular complex consisting of α-(KCNQ1) and β-subunits (KCNE1) and yotiao (AKAP-9), which recruits PKA and protein phosphatase 1 to the channel.

K, 11.1–hERG

The human erg protein (hERG or K, 11.1) is the pore-forming subunit of the rapid component of the cardiac delayed rectifier potassium current (I, Ks) responsible for AP repolarization. It is encoded by the hERG gene, which comprises 3 members, erg1, erg2, and erg3, displaying varying expression patterns in different tissues; herg1 is the best characterized. Structurally, hERG has 6 transmembrane domains (S1–S6), S4 being the voltage sensor, with cytosolic N and C termini. The N terminus, which contains a PAS (Per-Arnt-Sim) domain, strongly affects the biophysical properties of the channel. Functional hERG channels are tetramers with a pore region responsible for K+ current flow through the plasma membrane. As reviewed elsewhere, alternative transcription of hERG1 results in 2 identical proteins, hERG1a and hERG1b, that diverge only in their N termini. hERG1b can form channels alone or coassemble with hERG1a. A third variant of hERG1, also identical to hERG1a but with a modified C terminus is termed hERGuso. Expression of hERGuso reduces the number of channels at the sarcolemma and the current density. In contrast, coassembly with hERG1b alters channel kinetics increasing channel availability current magnitude. Mutations in hERG lead to long-QT syndrome type 2, a major cause of arrhythmias, as well as to short-QT syndrome type 2, which results in atrial and ventricular arrhythmias.

Even though heterologously expressed hERG channels are largely indistinguishable from native cardiac I, kr, a role for KCNE1 in this current was suggested by the diminished I, kr, in an atrial tumor line subjected to minK antisense suppression. Subsequently, McDonald et al showed that hERG and minK formed a stable complex and that the heteromultimerization regulated I, kr, activity. This provided additional support for the idea that minK, through the formation of heteromic channel complexes, is central to the control of the heart rate and rhythm. hERG has been shown to also coimmunoprecipitate with PKA, and similar to other cardiac K, channel subunits hERG interacts with SNAREs (soluble N-ethylmaleimide-sensitive-factor attachment protein receptors), which are proteins that are critical for synaptic vesicular secretion and possibly membrane protein trafficking. Recently, Ma et al identified 23 potential interacting proteins that may regulate...
cardiac $I_{Kr}$ through cytoskeletal interactions, G-protein modulation, phosphorylation, and downstream second messenger and transcription cascades. Fifteen such proteins were identified as hERG amino terminal (hERG-NT)-interacting proteins, including the caveolin-1, the zinc finger protein FHL2, and protein tyrosine phosphatase nonreceptor type 12 (PTPN12). The other 8 proteins were identified as hERG carboxylic terminal (hERG-CT)-interacting proteins, including the NF-kB-interacting protein myotrophin.\(^{168}\) Several unexpected binding partners were identified which greatly enhanced the dynamic modulation of $I_{Ks}$ as part of a macromolecular complex.\(^{168}\)

**KCNQ1–hERG Interactions**

After the pioneering studies of Sanguinetti et al.,\(^{154}\) it became clear that $I_{Kr}$, the delayed rectifying K current responsible for cardiac repolarization, is mediated by 2 distinct currents, $I_{Kr}$ and $I_{Ks}$, which work together to produce cardiac repolarization and control the APD. Recent results suggest that in addition to their voltage-dependent interactions, these 2 channels also interact at the molecular level.\(^{174}\) For example, studies in both transgenic LQT rabbit cardiomyocytes and stable, heterologous cell lines reported that hERG and KCNQ1 underwent reciprocal, functional downregulation in that coexpression of wild-type or dominant-negative pore mutants of KCNQ1 significantly reduced hERG currents, and vice versa.\(^{175}\) More recently, the same laboratory conducted acceptor photobleach Förster resonance energy transfer experiments and demonstrated that the intermolecular KCNQ1–hERG interactions are direct and mediated by their respective COOH termini.\(^{174}\) In agreement with the above results, another group showed that KCNQ1 preferentially communoprecipitated with mature hERG channels that were localized on the plasma membrane of HEK293 cells.\(^{176}\) However, the latter group demonstrated that although hERG channels undergo rapid endocytic degradation on exposure to hypokalemia, KCNQ1 channels are relatively insensitive to extracellular K$^+$ reduction.\(^{176}\) Thus, when hERG and KCNQ1 were expressed separately, exposure to 0 mmol/L K$^+$ for 6 hours completely eliminated the mature hERG channel expression but had no effect on KCNQ1. However, contrary to the transgenic rabbit data,\(^{174}\) the latter investigators showed that when hERG and KCNQ1 were coexpressed, KCNQ1 significantly delayed the hypokalemia-induced hERG loss.\(^{176}\) Also, hERG degradation led to a significant reduction in KCNQ1 in hypokalemia.\(^{176}\)

Therefore, although biophysical and pharmacological analyses conducted by both groups indicate that hERG and KCNQ1 closely interact with each other, their respective results seem to go in opposite directions: the former group concluded that coexpression of KCNQ1 significantly reduced hERG currents and vice versa,\(^{174}\) whereas the latter group concluded that coexpression of KCNQ1 protected hERG against hypokalemia, and hERG reduction reduced KCNQ1.\(^{176}\) Clearly additional studies will be necessary to resolve this controversy.

**Perspectives and Conclusions**

We have briefly reviewed research conducted over the past 20 years showing that cardiac ion channels may function as part of large macromolecular complexes. Such complexes play crucial roles the transcription, translation, oligomerization, trafficking, membrane retention, glycosylation, post-translational modification, turnover, function, and degradation of all cardiac ion channels known to date. In fact, macromolecular complexes are vital to a wide collection of cellular tasks. Some of these require physical contact among partner proteins, others do not. Understanding the structure and signaling dynamics of multiprotein assemblies is vital to understanding their function and is likely to shed light on how the heart functions in health and disease. However, we are still lacking a detailed knowledge of such processes, and of the role played by the myriad of ion channel molecular assemblies in the compartmentalization of ion channel function and the mechanisms underlying ion channel dysregulation, life-threatening cardiac arrhythmias, and SCD. This is a significant problem because both arrhythmias and SCD are among the most important causes of cardiovascular morbidity and mortality in the developed world. Clearly, many more studies are needed to establish new paradigms of cardiac electrophysiology integrating the large diversity of molecular interactions involved in the formation, targeting, and regulation of cardiac ion channels and their function, as well as the tissue-specific expression of the components of ion channel complexes not only in the working cardiac muscle of the atria and ventricles, but also the specialized pacemaking and conduction systems. Progress likely will come from the use of systems biology approaches, from the nanoscale all the way to the cellular and organ levels. Progress should also derive from the development and application of modern technologies enabling adequate spatiotemporal resolution to visualize and quantify the processes involved in the assembly and dynamic interactions of ion channel macromolecular complexes in living native myocytes from animal models, as well as in human stem-cell derived cardiomyocytes.

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**Disclosures**

None.

**References**


Tuning the electrical properties of the heart by differential trafficking

Arak


Rhythm for arrhythmia vulnerability in conditional Cx43 knockout mice.

M, van Rijen HV . Reduced heterogeneous expression of Cx43 results in localized in cardiac myocytes.

Malhotra JD, a zebrafish model of arrhythmogenic cardiomyopathy.

V, Yamoah EN, Chiamvimonvat N. Functional interaction with filamin-A and the inwardly rectifying potassium channel Kir2.1.

Ma D, Clegg D, Vandenberg C. Inward rectifier potassium channel Kir2.2 is associated with synapse-associated protein SAP97.


The glycolytic enzymes, glyceraldehyde-3-phosphate dehydrogenase, triose-phosphate isomerase, and pyruvate kinase are components of the K(ATP) channel macromolecular complex and regulate its function.


Heussner K, Yuan H, Neagoe I, Tarsov AF, Ashcroft FM, Schwappach B. Scavenging of 14-3-3 proteins reveals their involvement in the cell-surface transport of ATP-sensitive K+ channels.


Li J, Kline CF, Hund TJ, Anderson ME, Mohler PJ. Ankyrin-B regulates Kir2.2 membrane expression and function in heart.


Hong M, Bao L, Kefaloyianni E, Aguillo-Pascual E, Chikouru H, Foster M, Taskin E, Zhandre M, Reid DA, Rothenberg E, Delmar M, Coetzee WA. Heterogeneity of ATP-sensitive K+ channels in cardiac myocytes: enrichment at the intercalated disk.


Niwa N, Nerbonne JM. Molecular determinants of cardiac transient outward potassium current (Ito) expression and regulation.


Pongs O, Schwarz JR. Ancillary subunits associated with voltage-dependent K+ channels. 


Bou-Assal E, Li H, Nerbonne JM. Molecular diversity of the repolarizing voltage-gated K+ currents in mouse atrial cells. 


O’Connell KM, Conti LR, Radeke CM, McGuire LM, Vandenberg CA. Comparative proteomic analysis, and triggered activity in mice expressing a dominant-negative Kv2 channel.


Marx SO, Kurokawa J, Reiken S, Motohke D, Armento J, Marks AR, Kass RS. Requirement of a macromolecular signaling complex for beta adrenergic receptor modulation of the KCNQ1-KCNEM1 potassium channel.


Nerbonne JM. Molecular basis of functional voltage-gated K+ channel diversity in the mammalian myocardium.


Nerbonne JM, Kass RS. Molecular physiology of cardiac repolarization. 


Jerring HH, Qian JM, Pfaffinger PJ. Modulation of Kv4.2 channel expression and gating by dipetidyl peptide 10 (DPP10). 


Schulte U, Müller CS, Fakler B. Ion channels and their molecular environments–glimpses and insights from functional proteomics. 


Marionneau C, Townsend RR, Nerbonne JM. Proteomic analysis highlights the molecular determinants of native Kv4.2 channel macromolecular complexes. 


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