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Differential Distribution of Cardiac Ion Channel Expression as a Basis for Regional Specialization in Electrical Function

Gernot Schram, Marc Pourrier, Peter Melnyk, Stanley Nattel

Abstract—The cardiac electrical system is designed to ensure the appropriate rate and timing of contraction in all regions of the heart, which are essential for effective cardiac function. Well-controlled cardiac electrical activity depends on specialized properties of various components of the system, including the sinoatrial node, atria, atrioventricular node, His-Purkinje system, and ventricles. Cardiac electrical specialization was first recognized in the mid 1800s, but over the past 15 years, an enormous amount has been learned about how specialization is achieved by differential expression of cardiac ion channels. More recently, many aspects of the molecular basis have been revealed. Although the field is potentially vast, an appreciation of key elements is essential for any clinician or researcher wishing to understand modern cardiac electrophysiology. This article reviews the major regionally determined features of cardiac electrical function, discusses underlying ionic bases, and summarizes present knowledge of ion channel subunit distribution in relation to functional specialization. (*Circ Res.* 2002;90:939-950.)

Key Words: ion channels ■ molecular biology ■ conduction ■ cardiac arrhythmias ■ antiarrhythmic drugs

Cardiac function depends on the appropriate timing of contraction in various regions, as well as on appropriate heart rate. To subserve these functions, electrical activity in each region is adapted to its specialized function. Regionally specialized cardiac electrical function was recognized in the mid 1800s, when Stannius¹ demonstrated that ligatures in the superior vena caval sinus region of the frog caused cardiac asystole, with the sinus continuing to beat. With the widespread application to cardiac ion channel study of patch-clamp methodologies in the 1980s and molecular biology in the 1990s, many underlying mechanisms have been unraveled. The present article reviews the major regionally determined features of cardiac electrical function and the present knowledge regarding ionic and molecular bases.

Overview of Regional Functional Specificity

Figure 1 illustrates typical regional action potential (AP) properties in the heart. The normal cardiac impulse originates in the sinoatrial node (SAN) and propagates through the atria to reach the atrioventricular node (AVN). From the AVN, electrical activity passes rapidly through the cable-like His-Purkinje system to reach the ventricles, triggering cardiac pumping action. Figure 2 shows the ionic currents involved in a schematic cardiac AP, provides standard abbreviations for currents and their corresponding subunits, and summarizes principal localization data discussed elsewhere in the present review.

Ionic and Molecular Basis of Functional Specificity

Sinoatrial Node

Cellular Electrophysiology and Function

The SAN, located in the right atrial (RA) roof between the venae cavae,² is specialized for physiological pacemaker function. Heart rate control is achieved through autonomic regulation of SAN pacemaking. SAN APs have a relatively positive maximum diastolic potential (MDP) of ≈ -50 mV, a small phase 0 upstroke velocity (\dot{V}_{\max} , <2 V/s),³ and prominent phase-4 depolarization maintaining SAN pacemaker dominance. The cell type changes from the typical nodal cell at the center of the SAN to the atrial cell toward the periphery.³ The longest AP durations (APDs) are in the central pacemaking zone, preventing invasion by ectopic impulses and preserving SAN dominance.⁴ The SAN contains both spider and spindle pacemaker cell types.⁵ Spider cells have a faster intrinsic rate, a less negative MDP, and a longer APD, suggesting they are primary pacemaking cells of the central node. Cholinergic and β -adrenergic stimulation slow and accelerate spontaneous SAN activity, respectively. Electrical coupling to the atrium is designed to drive the large atrial muscle mass while insulating the SAN from hyperpolarizing atrial muscle influences.⁶ SAN dysfunction causes bradyarrhythmias that are associated with syncope but rarely with death.⁷

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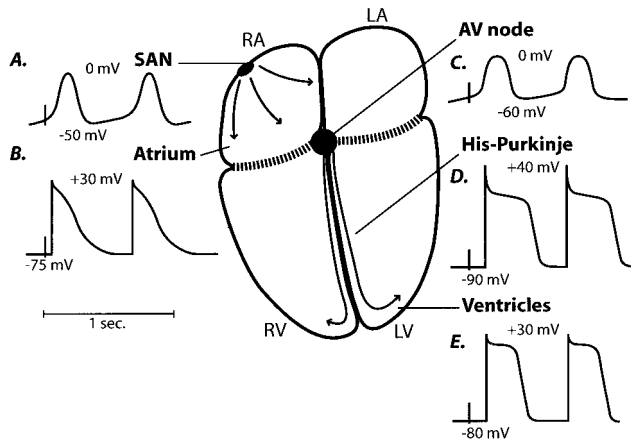


Figure 1. Schematic diagram of AP properties in different regions of the heart.

Ionic Mechanisms

Ionic properties underlying SAN function are indicated in Figure 3. Many varieties of time-dependent currents contribute to SAN pacemaking.⁸ A key time-dependent inward current, sometimes called the pacemaker current, is the

nonselective cation current (I_f).^{9,10} I_f density is $\approx 70\%$ greater in spider than in spindle cells.⁵ Several other currents flowing between the time of MDP and the phase-0 take off, including L-type Ca^{2+} current (I_{CaL}), T-type Ca^{2+} current (I_{CaT}), and the delayed rectifier K^+ current (I_K), influence pacemaking activity: inward Ca^{2+} current activation and outward K^+ current deactivation contribute to diastolic depolarization.⁸⁻¹⁰ I_{CaT} is particularly large in the SAN. One study found SAN pacemaker cells to lack the background K^+ current predominantly governing MDP (I_{K1}) and the transient outward current (I_{to}).¹¹ The lack of I_{K1} explains the positive MDP of SAN cells. A smaller rapid I_K component (I_{Kr}) in central SAN cells compared with peripheral cells may contribute to their more positive MDP and longer APD.¹² A smaller sustained I_{to} component may also contribute to longer APD in central SAN.¹³ I_{CaL} underlies AP upstrokes in primary SAN pacemaking tissue.^{10,11} The Na^+ current (I_{Na}) may contribute to subsidiary pacemaker activity in peripheral regions, providing a backup mechanism.¹⁴ A sustained inward component (I_{st}) related to I_{CaL} may also contribute to SAN depolarization,¹¹ but this remains controversial.¹⁵

Autonomic regulation of I_f and I_{CaL} controls heart rate. β -Adrenergic stimulation positively shifts I_f activation volt-

Principal Ion-channel Subunits and their Localization

Subunit	Corresponding Current	Primary Function	Demonstrated Localization	Abbreviations: Subunits: HCN=hyperpolarization-activated, cyclic-nucleotide binding channel subunit; Kir=inward-rectifier K^+ -channel subunit; ERG=ether-a-go-go related channel subunit; MiRP1=minK-related channel subunit-1; KvLQT1=Long-QT Syndrome-1 related channel subunit; minK=minimal K^+ -channel subunit; Kv=voltage-gated K^+ -channel subunit; KChIP2=Kv-channel interacting subunit-2; Ca_v =voltage-gated Ca^{2+} -channel subunit; Na_v =voltage-gated Na^+ -channel subunit; Cx=connexin hemichannel subunit. Currents: I_f =“funny” current (also called “ I_h ” or hyperpolarization-activated current); I_{K1} =inward-rectifier K^+ -current; I_{KACH} =acetylcholine-dependent current; I_{Kr} =rapid component of delayed-rectifier current (I_K); I_{Ks} =slow component of I_K ; I_{to} =transient outward K^+ -current; I_{Kur} =ultrarapid I_K ; I_{CaL} =L-type Ca^{2+} -current; I_{CaT} =T-type Ca^{2+} -current; I_{Na} = Na^+ -current; I_{GJ} =gap-junctional current. Tissues: SAN=sinoatrial node; AVN=atrioventricular node; V=ventricle, A=atrium; PF=Purkinje fibre; LA=left atrium; RA=right atrium; epi=epicardium; endo=endocardium.
HCN	I_f (pacemaking)	Diastolic depolarization	SAN>>PF>A>V	
Kir2.1	I_{K1}	Resting potential, terminal repolarization	V>A>>SAN	
Kir3.1/3.4	I_{KACH}	Mediates acetylcholine effects	SAN>A>>V	
ERG	I_{Kr} (α -subunit)	Phase-3 repolarization	Present in all tissues. LA>RA; ?V>PF	
MiRP1	Modulates I_{Kr} , I_f , I_{to}	?	SAN>>A>V	
KvLQT1	I_{Ks} (α -subunit)	Phase-3 repolarization (esp. with β -adrenergic stimulation, I_{Kr} inhibition)	Abundant in A and V. ?V>PF. ?Dominant-negative isoform in M-cells>epi or endo	
minK	I_{Ks} (β -subunit)	Necessary to form I_{Ks} with KvLQT1.	SAN>>A>V	
Kv4.2/4.3	I_{to} (α -subunit)	Early (phase-1) repolarization	Present in A and V. Species-specific. ?V>PF.	
Kv1.4	I_{to} (α -subunit)	Early (phase-1) repolarization	Important in some species (rabbit). ?Endo dominance (ferret).	
KChIP2	I_{to} (β -subunit)	Necessary to form I_{to} .	Epi>endo in man and dog.	
Kv1.5/3.1	I_{Kur}	Phase 1-2 repolarization.	Atrial-specific. (Kv1.5 man; Kv3.1 dog).	
$Ca_v1.2$	I_{CaL} (α -subunit)	Maintenance of plateau. Electromechanical coupling. Automaticity, conduction SAN, AVN	SAN>A. ?V>PF.	
$Ca_v1.3$	I_{CaL} component	Role in SAN function in mice.	?Weakly expressed in SAN, A.	
$Ca_v3.1-3.3$	I_{CaT}	?Role in pacemaking	SAN>>A. ?PF>V.	
$Na_v1.5$	I_{Na}	Conduction A, V, PF	Strong in A, V. Absent in compact AVN.	
Cx40,43,45	I_{GJ}	Intercellular conduction	Cx43 strong in A, V, PF; absent in central SAN, AVN. Cx40 strong in central SAN, also present in A. Cx45 in peripheral SAN, central AVN, PF.	

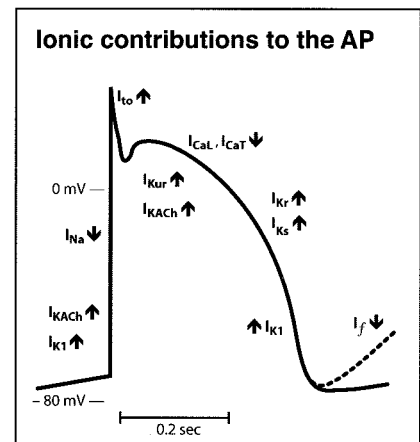


Figure 2. Principal cardiac ion channel subunits, corresponding currents, and localization. Inset shows schematic diagram of cardiac AP and currents involved in different phases. Outward currents correspond to upward arrows; inward currents correspond to downward arrows.

SA Node

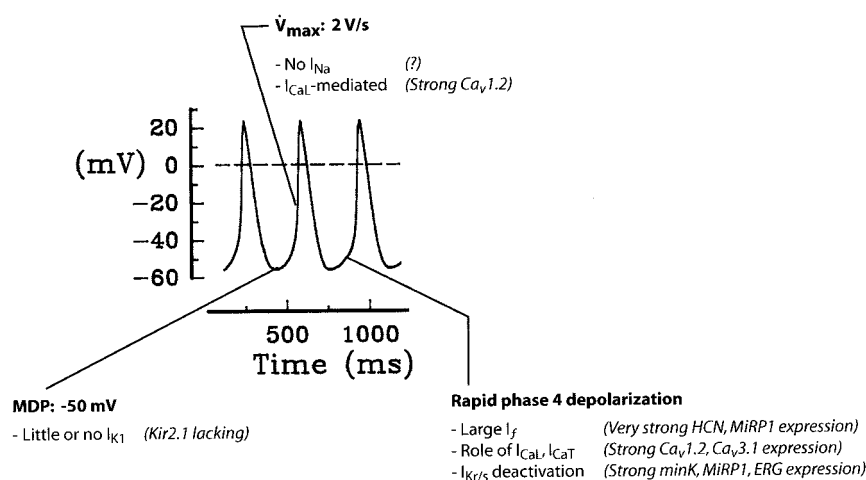


Figure 3. Characteristic AP properties of SAN cells. For each ionic property, the molecular basis believed to underlie ionic mechanisms is in italics and parentheses. APs are reproduced from Wu J, Schuessler RB, Rodefeld MD, Saffitz JE, Boineau JP. Morphological and membrane characteristics of spider and spindle cells isolated from rabbit sinus node. *Am J Physiol.* 2001;280:H1232–H1240, by permission of The American Physiological Society ©2001.

age dependence, accelerating diastolic depolarization.^{9,16} Adrenergically induced increases in I_{CaL} conductance also enhance SAN phase-4 terminal depolarization.^{9,10} Acetylcholine slows SAN activity by reducing I_f , activating the acetylcholine-sensitive K^+ current (I_{KACh}) and reducing I_{CaL} .⁹ The potency of acetylcholine for I_f inhibition is greater than that for I_{KACh} activation,¹⁷ which in turn is greater than that for I_{CaL} inhibition.⁹ I_{st} is also autonomously regulated.¹⁸

Molecular Basis

Hyperpolarization-activated cation channel (HCN)1-HCN4 cDNAs encode I_f -like currents.^{19–22} HCN transcripts are 25 times more abundant in the SAN than in Purkinje cells (PCs) and ≈ 140 times more abundant than in ventricular myocardium.²⁰ HCN1 protein and message and HCN4 transcripts are abundant in rabbit SAN, whereas HCN2 protein expression is weak, and HCN3 mRNA is absent.^{19–21} In the mouse, SAN HCN4 transcripts are abundant, HCN2 levels are moderate, and HCN1 levels are low.²² HCN1 and HCN2 coassemble to form functionally distinct channels.²³ The minK-related protein, MiRP1, increases the density and activation rate of I_f resulting from HCN expression.²⁴ MiRP1 mRNA is highly expressed in rabbit SAN, likely contributing to SAN pacemaker function.²⁴

Expression of Kir2.1, the predominant cardiac I_{K1} subunit, is very limited in ferret SAN, which is consistent with the virtual absence of I_{K1} .²⁵ I_{KACh} is formed by complexes containing Kir3.1 and Kir3.4 subunits.²⁶ Kir3.1 protein is present in rat, ferret, and guinea pig SAN.²⁷ Kir3.1 and m_2 -receptor proteins colocalize.²⁷ Kir3.4 protein is present in rat SAN.²⁷

Four subunits are believed to contribute to I_K : the ether-a-go-go-related (ERG) and MiRP1 subunits (thought to be α and β subunits of I_{Kr} , respectively)²⁸ and KvLQT1 and minK (α and β subunits of I_{Ks} , respectively),²⁹ although the role of MiRP1 remains controversial.³⁰ MinK transcripts are more abundant in the SAN than in the atrium or ventricle.²⁵ ERG protein and transcript are correlated with the presence of I_{Kr} in ferret³¹ and rabbit³² SAN.

Voltage-activated Ca^{2+} channel (Ca_v)3.1 and Ca_v 3.2 encode I_{CaT} α subunits.^{33,34} Ca_v 3.1 mRNA expression is 30-fold greater in mouse SAN than in mouse atrium.³⁵ Ca_v 3.2

expression is lower than Ca_v 3.1 expression, but it is also greater in the SAN.³⁵ Ca_v 1.2 and Ca_v 1.3 are I_{CaL} α subunits. Ca_v 1.3 mRNA expression is low in mouse SAN and atrium,³⁵ but Ca_v 1.3 knockout creates marked SAN dysfunction.³⁶ Ca_v 1.2 transcripts are more numerous and are more strongly expressed in the SAN than in the atrium.³⁵ Subunits β and $\alpha_2\delta$ modulate the density, kinetics, and activation/inactivation of I_{CaL} .³⁷ Little is known about their cardiac localization.

Gap-junctional hemichannel connexin (Cx) proteins are the basis of intercellular electrical coupling.³⁸ The SAN is shielded against hyperpolarizing atrial influences by compartmentalization of Cx expression.⁶ Many studies report that Cx43, the major cardiac Cx, is absent in the central SAN.^{6,27,39,40} Cx43 has been detected in the SAN of rabbits,⁴¹ hamsters,⁴² and dogs.⁴³ Cx45 and Cx40 are expressed in the SAN of rabbit and human hearts.^{6,44} Cx46 is present in rabbit SAN.⁴⁰ In canine SAN, 55% of the cells express Cx40 alone; 35% express Cx43, Cx45, and Cx40; and 10% show no Cxs.⁴³ Cells expressing all 3 connexins are located in bundles abutting atrial tissue, whereas Cx40-expressing cells are located in the central SAN.⁴³ Myocytes coexpressing Cx40, Cx43, and Cx45 extend from the SAN into the atrium, transmitting pacemaker impulses that drive the atrium.^{43,45}

Atrium

Cellular Electrophysiology and Function

The MDP in multicellular atrial preparations is ≈ -80 mV.^{46,47} Isolated atrial-myocyte MDP averages ≈ -70 mV.^{48,49} Atrial APs have MDPs ≈ 5 to 10 mV less negative than ventricular myocytes, exhibit slower phase-3 repolarization, and have little or no spontaneous phase-4 depolarization.

Spatial atrial AP/APD heterogeneity occurs within and between atrial regions^{50–53} and plays a role in atrial reentrant arrhythmias.⁵³ RA APD decreases progressively from the crista terminalis to the pectinate muscles,⁵¹ helping to “stream” the impulses from the SAN toward the AVN.⁵⁴ Rapid conduction follows fiber orientation in thicker bundles.⁵⁵ The APD and effective refractory period (ERP) are shorter in the left atrial (LA) free wall than in the RA.⁴⁹ In guinea pigs, cells from LA sleeves around proximal pulmo-

ATRIUM

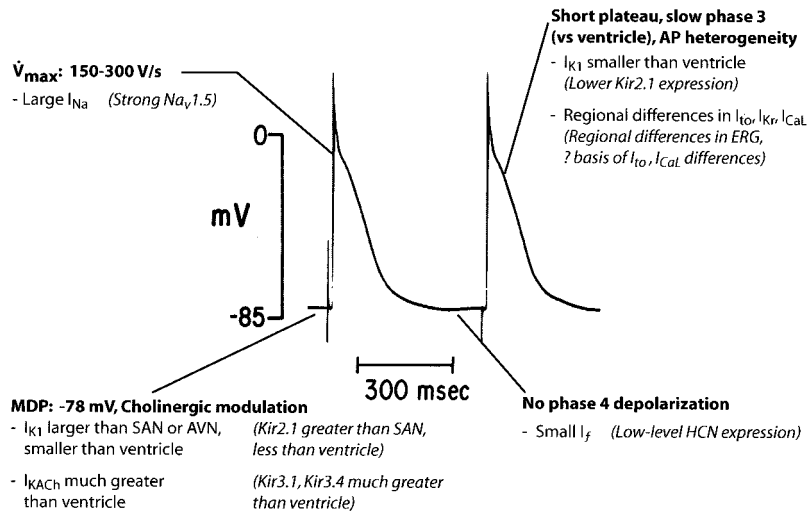


Figure 4. Basis of atrial cell AP properties. APs are reproduced from Spach MS, Dolber PC, Anderson PA. Multiple regional differences in cellular properties that regulate repolarization and contraction in the right atrium of adult and newborn dogs. *Circ Res.* 1989;65:1594–1611, by permission of the American Heart Association ©1989.

nary veins have APs similar to those in atrial myocytes, whereas more distally located cells have less negative MDP, shorter APD, and slow pacemaker activity.⁵⁶

Animal models^{57–59} and clinical studies⁶⁰ suggest an important role of the LA in atrial fibrillation. This may partly be due to accelerated LA repolarization,⁴⁹ which shortens ERPs, favoring reentry.⁶¹ LA pulmonary vein activity also triggers atrial fibrillation.⁶² In guinea pigs, pulmonary vein cells generate atrial tachycardias that are due to digitalis-induced triggered activity.⁶³ Parasympathetic stimulation shortens atrial APD in a spatially heterogeneous fashion,⁶⁴ producing important profibrillatory effects.⁶⁵

Ionic Mechanisms

The ionic mechanisms of atrial cell APs are summarized in Figure 4. I_f is present in atrial myocytes.^{66,67} A role for I_f in atrial ectopy has been suggested,⁶⁶ but atrial I_f function has been questioned because of limited activation at atrial MDP.⁶⁷ Atrial cells have large inward I_{Na} ,⁶⁸ providing energy for rapid conduction.

Atrial I_{K1} is 6- to 10-fold smaller than ventricular I_{K1} ,^{69,70} explaining the less negative atrial MDP and slower phase-3 repolarization. Ultrarapid delayed rectifier current (I_{Kur}), activating two orders of magnitude faster than I_{Kr} , has been described in rat,⁷¹ mouse,⁷² human,⁷³ and canine⁷⁴ atria. In humans and dogs, I_{Kur} is present in atria but not in ventricles.^{75,76} Atrial I_K includes both I_{Kr} and the slow component, I_{Ks} .^{77–79} Unlike normal ventricular myocytes, in which I_{CaT} is lacking in the absence of cardiac hypertrophy,⁸⁰ I_{CaT} is readily detectable in atrial myocytes⁴⁸ and may be important in atrial tachycardia-induced ionic remodeling.⁸¹ Atrial tachyarrhythmias and heart failure produce discrete atrial ionic remodeling,^{48,82,83} which is important in arrhythmogenesis.⁶¹ A recent study suggests that atrial tachycardia causes ionic remodeling and afterdepolarizations in pulmonary vein myocytes.⁸⁴ A number of discrepancies make that study difficult to interpret; these discrepancies include an I_{K1} reversal potential of -40 mV in cells with a resting potential of -65 mV, the simultaneous measurement of inward and outward currents with similar kinetics at the same test potentials with no

attempt to isolate components, and the generation of 25-mV delayed afterdepolarizations by transient inward currents <10 pA.

Myocytes from different RA regions show discrete ionic current distributions that explain their AP properties.⁵² LA free-wall myocytes have larger I_{Kr} compared with RA, accounting for their shorter APDs and ERPs.⁴⁹ I_{KACH} density is ≈ 6 times greater in the atrium than in the ventricle.⁸⁵

Molecular Basis

HCN2 and HCN4 are expressed in the atrium.⁸⁶ HCN4 message levels are much lower in the atrium than in the SAN.²¹

Kir2.1 is the most abundant Kir2-family (I_{K1}) subunit mRNA in the atrium and ventricle and is equally expressed in each.⁷⁰ Kir2.3 transcripts are more concentrated in human atrium than ventricle, and Kir2.2 transcripts are equal and sparse in both.⁷⁰ Kir2-subunit mRNA expression does not account for atrioventricular I_{K1} differences. Kir2.1 protein expression is $\approx 80\%$ greater in the ventricle than in the atrium, whereas Kir2.3 protein expression is 228% greater in the atrium.⁸⁷ Kir2.3 protein localizes to transverse tubules of most atrial but few ventricular cells, whereas the converse is true of Kir2.1.⁸⁷ The role of these atrioventricular differences in Kir2 protein expression in the much weaker atrial I_{K1} is uncertain.

Kir3.1 mRNAs are expressed strongly in rat atria but not ventricles,^{88,89} and Kir3.1 and Kir3.4 proteins are abundant in the atrium and sparse in the ventricle,²⁷ consistent with predominantly atrial I_{KACH} expression.⁸⁵ Recent work suggests that homomeric Kir3.4 channels may also contribute to atrial I_{KACH} .^{90,91}

The principal subunits thought to encode I_{to} include Kv1.4, Kv4.2, and Kv4.3.⁹² Kv4.2 contributes to rat atrial I_{to} ,⁹³ localizing to the sarcolemma and T tubules.⁹⁴ Kv1.4 transcript expression is stronger in rat atrium than ventricle,⁹⁵ but Kv1.4 protein is almost undetectable in both.⁹⁶ In rabbit atrium, Kv1.4 is a major contributor to I_{to} , whereas in human atrium, I_{to} is encoded entirely by Kv4.3.⁹⁷

The molecular basis of atrial I_{Kur} varies widely among species.⁹⁸ Kv1.2 and Kv1.5 contribute to rat atrial I_{Kur} .⁹³ Human atrial I_{Kur} is encoded by Kv1.5, with no corresponding component in the ventricle.⁹⁹ Kv3.1 is the molecular basis of canine atrial I_{Kur} , and like the corresponding current, it is absent in the ventricle.⁷⁶

KvLQT1 transcripts are abundant in ferret RA.¹⁰⁰ MinK is less abundant in the atrium than in the SAN.¹⁰⁰ ERG mRNA is abundantly expressed in the atrium, as is the longer (ERG_{1a}) variant, with larger expression in the ventricle versus atrium in humans and larger expression in the atrium versus ventricle in rats.¹⁰¹

ERG protein levels in dogs are larger in the LA than in the RA, consistent with a larger LA I_{Kr} .⁴⁹ No information is available about the molecular basis of intra-atrial regional differences in I_{to} and I_{CaL} .⁵² Cardiomyocytes in pulmonary veins contain Kir2.1 subunits and show I_{K1} -like currents,¹⁰² but otherwise, little is known about their molecular electrophysiology.

$Ca_v3.1$ and $Ca_v3.2$ transcripts are found in mouse atrium,³⁵ consistent with the atrial presence of I_{CaT} .⁴⁸ $Ca_v1.2$ transcripts are abundant in the atria, and their downregulation is believed to be central to atrial electrical remodeling.^{103,104} The Na^+ channel α subunit, $Na_v1.5$, is abundantly expressed in atrial myocytes, on the atrial surface, and in T-tubular membranes and intercalated disks, consistent with large I_{Na} .¹⁰⁵

Cx43 protein is present on bovine, guinea pig, and human atrial myocytes,^{106–108} with a distinct transitional zone containing interdigitating Cx43-expressing atrial and Cx43-lacking nodal cells at the periphery of the SAN.^{45,106,108} Canine and rabbit RA gap junctions contain mainly Cx40 and Cx43 and less Cx45.^{39,109} Cx40 expression in the atrium is much stronger than in the ventricle (where it is virtually undetectable) in humans, rabbits, guinea pigs, and mice.^{107,109–111} Cx40 is more abundant in human RA than LA.¹⁰⁷

Atrioventricular Node

Cellular Electrophysiology and Function

The primary function of the AVN is to govern the ventricular response to supraventricular activation. AVN cells have low excitability and postrepolarization refractoriness,¹¹² which limit the maximum number of impulses that can traverse to the ventricles¹¹³ and prevent dangerously rapid ventricular rates in response to supraventricular tachyarrhythmias.

The AVN has a complex 3D structure. APs from intact AVN have slow upstrokes and small amplitudes.¹¹⁴ Within the compact AVN, MDPs are ≈ -64 mV, phase-4 depolarization results in takeoff potentials of ≈ -60 mV, and \dot{V}_{max} is < 20 V/s.¹¹⁵ Cell types include N cells in the compact node and NH cells at the junction with the His bundle.¹¹⁵ A modern classification divides the AVN into a transitional cell area, compact node, posterior nodal extension, and lower nodal cell bundle.¹¹⁶

Ovoid and rod-shaped cells have been isolated from the compact AVN.¹¹⁷ Ovoid cells have N- or NH-like APs showing postrepolarization refractoriness and no AP abbreviation with increased frequency, less negative MDPs, faster diastolic-depolarization, and smaller \dot{V}_{max} than those in rod-shaped cells. Rod-shaped cells display APs intermediate

AVN (ovoid, N-cells)

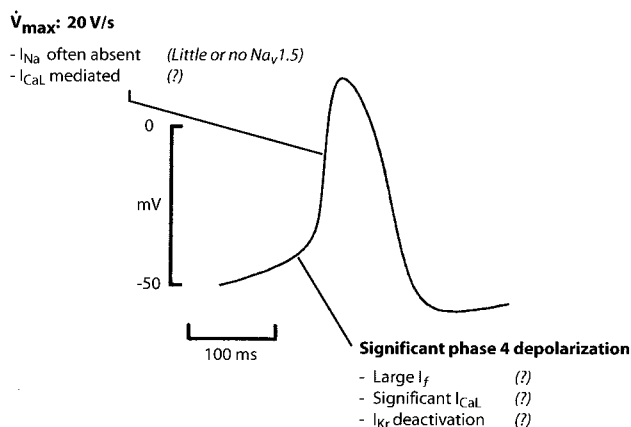


Figure 5. Basis of AVN cell AP properties. AP is reproduced from Munk AA, Adjemian RA, Zhao J, Ogbaghebriel A, Shrier A. Electrophysiological properties of morphologically distinct cells isolated from the rabbit atrioventricular node. *J Physiol.* 1996;493:801–818, by permission of The Physiological Society ©1996.

between typical AVN and atrial cells (AN type).¹¹⁷ AVN cells have pacemaking activity,^{117,118} particularly in the midnodal and lower nodal regions.¹¹⁹ Spontaneous activity in AN cells is suppressed by atrial electrotonic influences.¹²⁰

AV node reentrant arrhythmias were classically related to the presence of dissociable AVN pathways,¹²¹ which are typically manifested clinically as a faster conducting pathway with a longer refractory period and a slower conducting pathway with more brief refractoriness.¹²² Although the detailed physiology is not completely clear, there is evidence that the posterior nodal extension may form the slow pathway substrate.¹¹⁶

Ionic Mechanisms

The ionic basis of AVN properties is illustrated in Figure 5. I_f is present in 95% of ovoid cells versus $\approx 10\%$ of rod-shaped cells, and I_f density is ≈ 25 -fold larger in ovoid cells, which is consistent with the much greater ovoid cell pacemaker activity.¹¹⁷ I_{Na} and I_{to} are present in few ovoid cells but in almost all rod-shaped cells.¹¹⁷ I_{CaL} underlies the compact AVN AP upstroke.¹²³ 4-Aminopyridine inhibits spontaneous AVN APs, which is consistent with a role for I_{to} in AVN pacemaking.¹²⁴ I_{to} elimination in transgenic mice causes atrioventricular block.¹²⁵

I_K deactivates faster in AVN than in ventricular myocytes.¹²⁶ Contrary to the SAN, where both I_{Kr} and I_{Ks} are important, I_{Kr} predominates in the AVN.¹²⁷ I_{Kr} activation contributes to AVN repolarization and deactivation to diastolic depolarization.¹²³ There is little I_{K1} in the AVN,¹²³ consistent with its positive MDP.

Molecular Basis

Data regarding ion channel subunit distribution in the AVN are limited. As opposed to transitional or lower nodal cells, midnodal cells of the rabbit AVN display little or no Na^+ channel α subunit or Cx43 protein.¹²⁸ Cx43 expression is sparse or absent in the AVN.^{129–132} Low-level Cx43 expression colocalizes with Cx40 in the rat.¹³² Targeted disruption

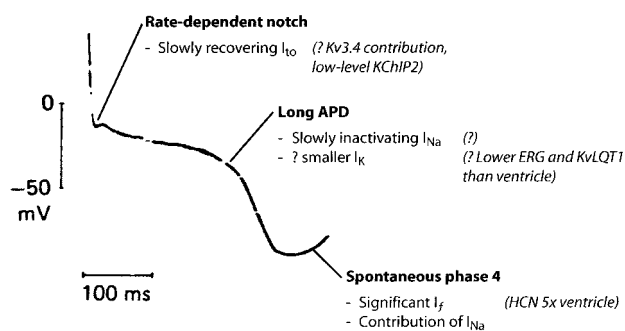
Purkinje cells

Figure 6. Basis of PC AP properties. AP is adapted from Callewaert G, Carmeliet E, Vereecke J. Single cardiac Purkinje cells: general electrophysiology and voltage-clamp analysis of the pace-maker current. *J Physiol*. 1984;349:643–661, by permission of The Physiological Society ©1984.

of Cx40-subunit expression impairs atrioventricular conduction in the mouse,^{133–135} although much of the delay is attributable to slowing in the ventricular conduction system.¹³⁶ Cx45 is strongly expressed in the rodent AVN and conducting system.¹³⁷

His-Purkinje System

Cellular Electrophysiology and Function

PCs forming the bundles of His and the Purkinje system are specialized for rapid conduction. PC MDP is 5 to 10 mV more negative (averaging ≈ -90 mV) than is working ventricular MDP.^{138,139} \dot{V}_{\max} is also greater in PCs (≈ 400 to 800 V/s) than in the ventricle (150 to 300 V/s), and the PC plateau voltage is lower.^{138,139} APD is more prolonged in PCs than in ventricular muscle at slow rates.^{140,141} PCs show prominent phase-4 depolarization, providing ventricular escape pacemakers.¹⁴² PCs preferentially generate drug-induced early afterdepolarizations that excite adjacent ventricular muscle,¹⁴¹ likely explaining endocardial early afterdepolarizations that trigger torsade de pointes arrhythmias.^{143,144}

Ionic Mechanisms

Multicellular Purkinje fiber preparations were used for classic voltage-clamp studies because of favorable geometry; however, because of the difficulty of isolating PCs, much less work has been done recently. Ionic bases for PC AP properties are illustrated in Figure 6. Both I_{CaL} and I_{CaT} are present in PCs, with I_{CaT} being quite substantial.^{145,146} PCs have a smaller I_{CaL} than ventricular myocytes, consistent with their less positive plateau.¹⁴⁷ I_{CaT} inhibition does not affect Purkinje fiber automaticity, suggesting that I_{CaT} may not be important for PC pacemaking.¹⁴⁸

Two studies showed smaller I_{K1} in PCs than in ventricular muscle,^{147,149} whereas one study showed no significant differences.¹⁵⁰ I_{to} in human¹⁵⁰ and canine¹⁵¹ PCs displays striking differences compared with ventricular myocytes, including sensitivity to 10 mmol/L tetraethylammonium, ≈ 9 -fold greater sensitivity to 4-aminopyridine, and slower reactivation. PC I_K resembles ventricular and atrial I_K .¹⁵² I_f is observed in human PCs, consistent with their pacemaker activity.¹⁵⁰ Slowly inactivating I_{Na} may contribute to maintaining PC

APD, especially at slow rates.¹⁵³ Downregulation of I_{to} and I_{K1} in PCs of dogs with congestive heart failure enhances their sensitivity to I_{Kr} blocker-induced APD prolongation, possibly explaining the increased risk of drug-induced long-QT syndrome in patients with congestive heart failure.¹⁵⁴

Molecular Basis

HCN1 and HCN4 transcripts are expressed in rat and rabbit Purkinje fibers.²⁰ HCN expression in PCs is lower than that in the SAN but higher than that in ventricles.²⁰

Canine Purkinje fibers do not significantly express Kv4.2 or Kv1.4 mRNA, and Kv4.3 mRNA levels in PCs are similar to those in the midmyocardium.¹⁵⁵ K^+ channel interacting protein (KChIP)2 mRNA is denser in myocardium than in PCs, whereas Kv3.4 is more concentrated in PCs,¹⁵⁵ compatible with their tetraethylammonium-sensitive I_{to} .¹⁵² ERG and KvLQT1 mRNA levels are lower in PCs,¹⁵⁵ suggesting that smaller I_K may contribute to their longer APD. $Ca_v1.2$ mRNA levels are lower in PCs,¹⁵⁵ consistent with their smaller I_{CaL} .¹⁴⁷ $Ca_v3.1$, $Ca_v3.2$, and $Ca_v3.3$ expression is much greater in PCs than in the ventricle,¹⁵⁵ compatible with their large I_{CaT} .^{145,146}

Cx40 mRNA is 3 to 5 times more abundant in PCs than in the ventricle.^{39,44,156} Cx40 colocalizes with Cx43 in the rat cardiac conducting system.¹³² Cx45 in mouse and rat hearts is found only in the His-Purkinje system.¹⁵⁷ The extensive expression of Cx in Purkinje tissue may be crucial for very rapid conduction.

Ventricular Muscle

Cellular Electrophysiology and Function

MDPs of ventricular myocytes are ≈ -85 mV.^{138,139,158} The plateau is relatively positive, at ≈ 10 to 20 mV, and phase-3 repolarization is rapid. As in working atrial muscle, there is no significant phase-4 depolarization or automaticity.

Regional ventricular AP heterogeneity is well established. Compared with endocardium, epicardial APs show a smaller overshoot, a more prominent phase 1 followed by a notch (spike and dome), and a briefer APD, but MDP and \dot{V}_{\max} are not significantly different.¹⁵⁹ Epicardial-endocardial AP differences are crucial for the ECG T wave.¹⁵⁹ Midmyocardial cells (M cells) are a cell population in the deep subepicardium.^{160,161} Like PC APDs, M-cell APDs increase substantially at slow rates and have a larger \dot{V}_{\max} (≈ 300 V/s) than do endocardial and epicardial cells (≈ 200 V/s).¹⁶⁰ M-cell APs in the right ventricle (RV) compared with the left ventricle (LV) have a smaller upstroke, a deeper notch, and a shorter duration.¹⁶² In the rat, APD is shortest at the apex and longest in the septum, with intermediate values in the free wall.¹⁶³ Transmural ERP heterogeneity caused by differential M-cell APD prolongation may contribute to torsade de pointes by promoting transmural reentry,¹⁶⁴ particularly in the presence of hypokalemia, slow heart rates, and APD-prolonging drugs.¹⁶⁵

Ionic Mechanisms

The information available about the ionic bases of transmural AP heterogeneity in the ventricles is summarized in Figure 7. I_{to} differences between epicardium and endocardium were originally inferred from phase-1 repolarization properties.¹⁵⁹ I_{to} is larger in epicardium than endocardium for dogs, cats,

Transmural Ventricular heterogeneity

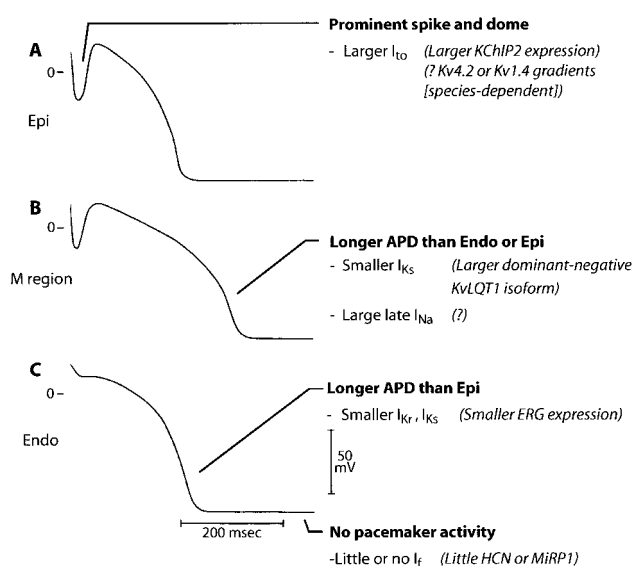


Figure 7. AP properties of ventricular epicardium, midmyocardium, and endocardium. APs are reproduced from Sicouri S, Antzelevitch C. A subpopulation of cells with unique electrophysiological properties in the deep subepicardium of the canine ventricle: the M cell. *Circ Res.* 1991;68:1729–1741, by permission of the American Heart Association ©1991.

rabbits, and humans.^{166–169} In guinea pigs, I_{Kr} and I_{Ks} are smaller in endocardial cells than in epicardial or M cells.¹⁷⁰ In cats and guinea pigs, I_K is larger in the epicardium,^{171,172} with I_{Kr} responsible for the difference in guinea pigs.¹⁷² The outward component of I_{K1} is smaller in cat epicardium¹⁷¹ but not guinea pig¹⁷² or dog¹⁷³ epicardium.

M-cell properties are not attributable to differences in I_{K1} or I_{to} .¹⁷⁴ Smaller I_{Ks} in M cells contributes to their longer APD.^{173,175} M cells also have a larger late I_{Na} than do epicardial or endocardial cells in dogs¹⁷⁶ but not in guinea pigs.¹⁷² RV M-cell APDs are shorter than LV M-cell APDs, possibly because of larger I_{to} and/or I_{Ks} in the RV.¹⁶² A smaller I_{Ks} in LV apical versus basal myocytes may underlie longer apical APD, although I_{Kr} appears larger at the apex.¹⁷⁷ Regional differences in outward I_{K1} ¹⁷⁸ and in I_{Kr} ¹⁷⁹ may be a significant determinant of VF.

Molecular Basis

HCN2 is the only isoform in rabbit ventricle, and its mRNA expression is minimal.²⁰ HCN4 mRNA has been detected in rat ventricle.²⁰ HCN2 and HCN4 have been detected in human ventricle but have not been quantified.¹⁸⁰ HCN1 and HCN3 were not detected in the ventricle.^{19,21} Low-level HCN expression in the ventricle is consistent with its lack of automaticity.

Kir2.1 is by far the most abundant Kir transcript in the human heart.⁷⁰ Antisense experiments and studies in Kir2.1 and Kir2.2 knockout mice indicate that Kir2.1 subunits are the major, but not only, component of I_{K1} .^{181,182}

I_{to} in rat ventricle is thought to be encoded predominantly by Kv4.2 and Kv4.3.^{96,183–185} Kv4.2 mRNA expression in the rat LV wall is correlated with the gradient in I_{to} density.⁹⁵ In ferret ventricle, the transmural I_{to} gradient is due to stronger

endocardial expression of Kv1.4 versus epicardial predominance of Kv4.2 and Kv4.3.¹⁸⁶ Kv4.3 underlies I_{to} in dog and human hearts.^{187,188} Kv4.2 mRNA is not detectable in canine¹⁸⁷ or human¹⁸⁹ ventricle. Kv4.2 is thought to encode the fast component and Kv1.4 is thought to encode the slow component of I_{to} in rodents.¹⁹⁰ Kv4.1 mRNA expression is very low, suggesting little importance for native cardiac I_{to} .⁹⁵

KChIP2 substantially increases functional expression and modifies inactivation of Kv4 subunits.¹⁹¹ KChIP2 expression is greater in the epicardium than in the endocardium, consistent with the transmural I_{to} gradient, whereas Kv4.3 is uniformly expressed across the wall.¹⁹² KChIP2 knockout virtually eliminates I_{to} .¹⁹³ KChAP may be a chaperone for Kv channels that form I_{to} .¹⁹⁴

Kv1.5 has been observed at the intercalated disk of human ventricular and atrial myocytes, but longitudinal membrane staining is seen only in the atrium,¹⁹⁵ perhaps accounting for atrium-specific expression of the corresponding current.^{75,99} Rat Kv2.1 is more abundant in the ventricle than in the atrium.⁹⁵ Kv2.1 may encode rat ventricular I_{Kur} , but there is poor correlation between Kv2.1 expression and I_{Kur} density in rat ventricle.¹⁹⁶

Human minK mRNA levels are not significantly different among epicardial, midmyocardial, and endocardial tissues.¹⁹⁷ However, a dominant negative KvLQT1 splice variant (isoform 2) is more strongly expressed in the midmyocardium, potentially accounting for lower I_{Ks} in M cells.¹⁹⁷ In the ferret, ERG protein expression is stronger in the epicardium.³¹ ERG mRNA is 1.5-fold more abundant than Kv4.3 in canine RV and is the most prevalent K^+ channel species in the heart,³² consistent with its prominent role in repolarization. MiRP1 is expressed sparsely in rabbit ventricle.²⁴ Along with recent studies showing limited effects of MiRP1 coexpression on ERG currents,³⁰ this observation raises questions about the role of MiRP1 in ventricular I_{Kr} .

$Ca_v1.2$ and I_{CaL} β and α_2/δ subunits are present in the human septum and LV.¹⁹⁸ $Na_v1.1$ and β_1 and β_2 subunits are expressed along the Z lines in adult rat cardiac myocytes.¹⁹⁹ β_1 subunits modulate I_{Na} , but β_2 -subunit function may be limited to cell adhesion.¹⁹⁹ As in the atrium, in the ventricles, $Na_v1.5$ is the principal Na^+ channel α subunit found on membranes and the T-tubular system and at the intercalated disk region.¹⁰⁵

Cx43 is the predominant Cx in the ventricles.^{107,111,156} Heterozygous knockout of Cx43 slowed ventricular conduction in adult mice, with minimal effects on the atrium, as reported in one study,¹¹¹ but did not affect conduction in mouse embryos in another.²⁰⁰ Homozygote Cx43 knockouts had severe impairment of ventricular conduction, consistent with a critical role in ventricular conduction that can be compensated in the heterozygote.²⁰⁰

Conclusions

A tremendous amount has been learned over the last 10 to 15 years regarding the ionic and molecular basis of cardiac regional electrical specialization. Nevertheless, many aspects remain unexplained. The molecular biology of ion channel expression in the AVN and Purkinje fibers remains largely unexplored. The basis of intra-atrial and intraventricular

regional variations in ion channel function remains poorly understood, and the distribution of ion channel subunits in specific cellular subtypes in complex regions such as the SAN and AVN remains largely unknown. Species differences in ion channel distribution are incompletely understood and complicate extrapolations of experimental findings to humans. The effects of disease states on regional ion channel function are virtually unknown. Targeted modulation of regional ion channel function by genetic engineering approaches may open up entirely new therapeutic vistas, and its feasibility has been demonstrated.²⁰¹

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