Is There a Need to Add Another Dimension (Time) to the Evaluation of the Arrhythmogenic Potential of New Drug Candidates In Vitro?

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Most drug therapy regimens expose the human body to a foreign chemical for several hours to days and even years. Hence, before a new drug is approved by regulatory agencies, extensive safety studies are conducted to ensure that exposure to the drug will not cause undesirable effects in patients. A major cause of adverse events and drug attrition is cardiovascular toxicity.\textsuperscript{1,2} Drug developers have attempted to identify these issues earlier in medicine development to reduce risks to human volunteers in clinical trials and costs of pursuing the development of unsafe drugs. In 2005, the International Conference on Harmonization of Technical Requirements for Registration of Pharmaceuticals for Human Use issued a guideline for the examination of new drug candidates in a series of in vitro and in vivo tests to assess their arrhythmogenic potential.\textsuperscript{3} Inhibition of the delayed rectifier potassium current ($I_{Kr}$) in the heart has been linked to the majority of drug-induced arrhythmias. As a result, in vitro safety testing has been focused on acute drug effects on $I_{Kr}$ or hERG, the potassium channel that underlies $I_{Kr}$.\textsuperscript{4} The development of high-throughput automated methods to measure hERG currents in heterologous expression systems has fueled the emphasis of in vitro testing on $I_{Kr}$ early in drug discovery and perhaps prevented the development of new medicines by discarding compounds prematurely. This testing paradigm has been challenged over the past several years with the realization that verapamil and a number of other drugs that inhibit $I_{Kr}$ acutely but instead inhibit its trafficking to the cell surface when applied for prolonged (overnight or longer) periods of time.\textsuperscript{5,6} More recently, Lu and colleagues\textsuperscript{7} showed that prolonged dofetilide exposure increased late sodium currents in mouse cardiomyocytes, human induced pluripotent stem cell–derived cardiomyocytes, and Chinese hamster ovary cells transfected with the cardiac sodium channel Nav1.5. Peak sodium currents were also increased, but sodium channel protein levels were unchanged. These findings prompted Yang and colleagues to examine the gating properties of sodium channels after a 5-hour exposure to dofetilide. Channel inactivation was shifted toward more positive potentials by $\approx 20$ mV, yielding window currents between $-60$ and $-40$ mV. Channel recovery from inactivation was faster, and the rate constants for fast and slow inactivation of macroscopic currents were increased. Taken together, these changes in channel gating are consistent with increased peak and late sodium currents. The mechanism by which the PI3K pathway regulates sodium channel gating remains to be determined. However, the results from Yang and colleagues show that it is conserved in mouse cardiomyocytes, human stem cell–derived cardiomyocytes, and hamster ovary cells. The protein kinase Akt, a downstream effector of PI3K, may be involved; the authors observed reduced Akt phosphorylation after prolonged exposure to dofetilide. In addition, the PI3K inhibitor LY294002 decreased Akt phosphorylation and increased late sodium currents in cells expressing Nav1.5.
Yang and colleagues also found that effects on late sodium currents were not limited to dofetilide or terfenadine. They reported that other \( I_{\text{Kr}} \) blockers also increased \( I_{\text{Na-L}} \) in Chinese hamster ovary cells transfected with Nav1.5. D-sotalol and E-4031, both methane sulfonanilides like dofetilide, increased \( I_{\text{Na-L}} \) after prolonged exposure. They also observed increased late sodium currents, although to a lower extent, with 3 unrelated drugs, the antipsychotics haloperidol and thiordizine and the antibiotic erythromycin. Finally, moxifloxacin and verapamil did not alter the amplitude of \( I_{\text{Na-L}} \). This range of effects on late sodium currents could significantly contribute to the variety of proarrhythmic activities of these \( I_{\text{Kr}} \) blockers. Increased late sodium currents are a known cause of cardiac arrhythmias. Several mutations in SCN5A, the gene encoding the cardiac sodium channel Nav1.5, underlie the long-QT syndrome type 3. These mutations lead to various levels of late sodium currents, all very small relative to peak current amplitudes (≤3%) but large enough to disrupt action potentials and to cause arrhythmias.

This article may show us the tip of the iceberg with regard to the effects of prolonged drug exposure on cardiac action potentials and their underlying ionic currents. Additional studies are warranted to determine the prevalence of drug effects on late sodium currents. Most early safety pharmacology studies on cardiac ion channels are performed on automated electrophysiology instruments. These instruments, however, generally do not have the sensitivity to measure late sodium currents, all very small relative to peak current amplitudes (≤3%) but large enough to disrupt action potentials and to cause arrhythmias.

The need to examine the effects of drug candidates on multiple cardiac ion channels and to review the current testing paradigm is the focus of a recently initiated public-private project called Comprehensive In Vitro Proarrhythmia Assay. This project proposes, in part, the examination of drug effects on various cardiac channels and their integration in silico by computer models of human cardiac electrophysiology, with the aim of proposing a new paradigm for the assessment of the proarrhythmic potential of new drugs. However, most cardiac ion channel assays and modeling efforts examine short-term exposure to drugs and do not consider prolonged or long-term effects. For example, they do not incorporate effects on channel trafficking, which have been well documented for several drugs and the hERG channel. However, recent studies point out the need to include binding kinetics to refine in silico models. The findings of Yang and colleagues are therefore timely and should stimulate discussions in the field of cardiac safety on the necessity to look at prolonged effects of drug candidates on the various determinants of cardiac excitability.

Disclosures

None.

References


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