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THE NONCLINICAL EVALUATION OF THE POTENTIAL FOR DELAYED  
VENTRICULAR REPOLARIZATION (QT INTERVAL PROLONGATION) BY HUMAN  
PHARMACEUTICALS

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NOTE FOR GUIDANCE ON

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VENTRICULAR REPOLARIZATION (QT INTERVAL PROLONGATION) BY HUMAN  
PHARMACEUTICALS

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# **THE NONCLINICAL EVALUATION OF THE POTENTIAL FOR DELAYED VENTRICULAR REPOLARIZATION (QT INTERVAL PROLONGATION) BY HUMAN PHARMACEUTICALS**

## **The Non-clinical Evaluation of the Potential for Delayed Ventricular Repolarization (QT Interval Prolongation) by Human Pharmaceuticals**

### **1. INTRODUCTION**

The assessment of the effects of pharmaceuticals on ventricular repolarization and proarrhythmic risk is the subject of active investigation. When additional data (non-clinical and clinical) are accumulated in the future, they will be evaluated and this guideline might be revised.

#### **1.1 Objective of the Guideline**

This guideline describes a non-clinical testing strategy for assessing the potential of a test substance to delay ventricular repolarization. This guideline includes information concerning non-clinical assays and integrated risk assessments.

#### **1.2 Background**

The QT interval (time from the beginning of the QRS complex to the end of the T wave) of the electrocardiogram (ECG) is a measure of the duration of ventricular depolarization and repolarization. QT interval prolongation can be congenital or acquired (e.g., pharmaceutical-induced). When ventricular repolarization is delayed and the QT interval is prolonged, there is an increased risk of ventricular tachyarrhythmia, including torsade de pointes, particularly when combined with other risk factors (e.g., hypokalemia, structural heart disease, bradycardia). Thus, much emphasis has been placed on the potential proarrhythmic effects of pharmaceuticals that are associated with QT interval prolongation.

Ventricular repolarization, determined by the duration of the cardiac action potential, is a complex physiological process. It is the net result of the activities of many membrane ion channels and transporters. Under physiological conditions, the functions of these ion channels and transporters are highly interdependent. The activity of each ion channel or transporter is affected by multiple factors including, but not limited to, intracellular and extracellular ion concentrations, membrane potential, cell-to-cell electrical coupling, heart rate, and autonomic nervous system activity. The metabolic state (e.g., acid-base balance) and location and type of cardiac cell are also important. The human ventricular action potential consists of five sequential phases:

- phase 0: The upstroke of the action potential is primarily a consequence of a rapid, transient influx of  $\text{Na}^+$  ( $I_{\text{Na}}$ ) through  $\text{Na}^+$  channels.
- phase 1: The termination of the upstroke of the action potential and early repolarization phase result from the inactivation of  $\text{Na}^+$  channels and the transient efflux of  $\text{K}^+$  ( $I_{\text{to}}$ ) through  $\text{K}^+$  channels.
- phase 2: The plateau of the action potential is a reflection of a balance between the influx of  $\text{Ca}^{2+}$  ( $I_{\text{Ca}}$ ) through L-type  $\text{Ca}^{2+}$  channels and outward repolarizing  $\text{K}^+$  currents.
- phase 3: The sustained downward stroke of the action potential and the late repolarization phase result from the efflux of  $\text{K}^+$  ( $I_{\text{Kr}}$  and  $I_{\text{Ks}}$ ) through delayed rectifier  $\text{K}^+$  channels.
- phase 4: The resting potential is maintained by the inward rectifier  $\text{K}^+$  current ( $I_{\text{K1}}$ ).

Prolongation of the action potential can result from decreased inactivation of the inward  $\text{Na}^+$  or  $\text{Ca}^{2+}$  currents, increased activation of the  $\text{Ca}^{2+}$  current, or inhibition of one or more of the

outward K<sup>+</sup> currents. The rapidly and slowly activating components of the delayed rectifier potassium current, I<sub>Kr</sub> and I<sub>Ks</sub>, seem to have the most influential role in determining the duration of the action potential and thus the QT interval. The human ether-a-go-go-related gene (hERG) and KvLQT1 gene encode pore-forming proteins KCNH2 and KCNQ1 that are thought to represent the α-subunits of the human potassium channels responsible for I<sub>Kr</sub> and I<sub>Ks</sub>, respectively. These α-subunit proteins can form hetero-oligomeric complexes with auxiliary β-subunits (i.e. MiRP and MinK gene products), which have been speculated to modulate the gating properties of the channel proteins. The most common mechanism of QT interval prolongation by pharmaceuticals is inhibition of the delayed rectifier potassium channel that is responsible for I<sub>Kr</sub>.

### **1.3 Scope of the Guideline**

This guideline extends and complements the “ICH Guideline on Safety Pharmacology Studies for Human Pharmaceuticals” (ICH S7A). This guideline applies to new chemical entities for human use and marketed pharmaceuticals when appropriate (e.g., when adverse clinical events, a new patient population, or a new route of administration raises concerns not previously addressed). Conditions under which studies are not called for are described in ICH S7A.

### **1.4 General Principles**

Principles and recommendations described in ICH S7A also apply to the studies conducted in accordance with the present guideline. *In vitro* I<sub>Kr</sub> and *in vivo* QT assays described in Sections 2.3.1 and 2.3.2 when performed for regulatory submission should be conducted in compliance with good laboratory practice (GLP). Follow-up studies described in Section 2.3.5 should be conducted in compliance with GLP to the greatest extent feasible.

*In vitro* and *in vivo* assays are complementary approaches; therefore, according to current understanding, both assay types should be conducted.

The investigational approach and evidence of risk should be individualized for the test substance, depending on its pharmacodynamic, pharmacokinetic and safety profiles.

## **2. GUIDELINE**

### **2.1 Objectives of S7B Studies**

The objectives of studies are to: 1) identify the potential of a test substance and its metabolites to delay ventricular repolarization, and 2) relate the extent of delayed ventricular repolarization to the concentrations of a test substance and its metabolites. The study results can be used to elucidate the mechanism of action and, when considered with other information, estimate risk for delayed ventricular repolarization and QT interval prolongation in humans.

### **2.2 Considerations for Selection and Design of Studies**

Non-clinical methodologies can address the following:

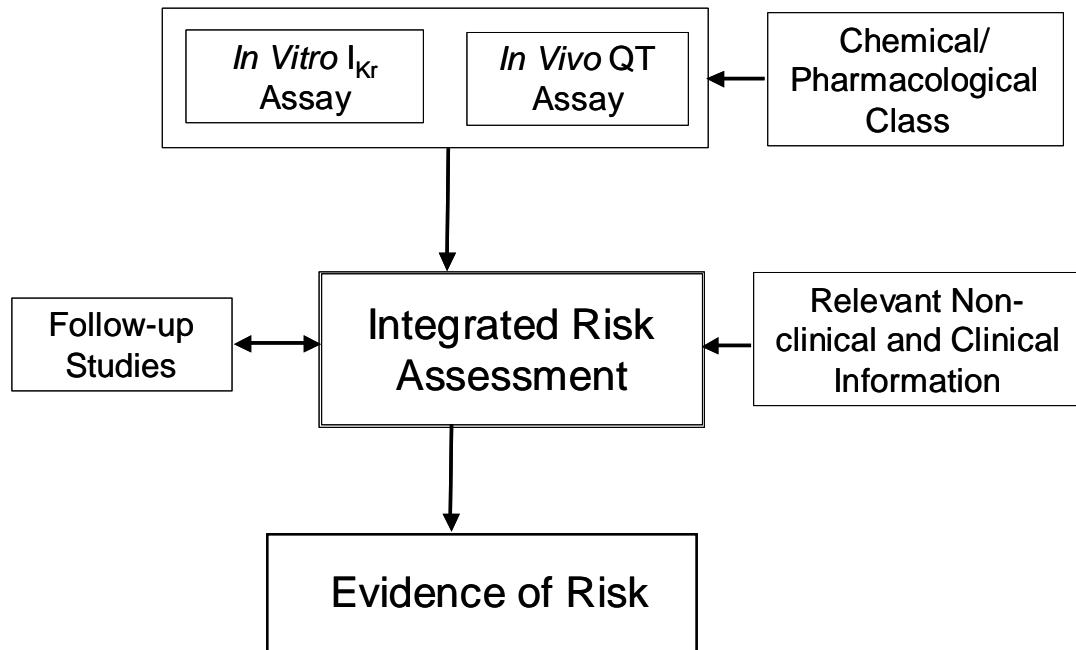
- Ionic currents measured in isolated animal or human cardiac myocytes, cultured cardiac cell lines, or heterologous expression systems for cloned human ion channels,
- Action potential parameters in isolated cardiac preparations or specific electrophysiology parameters indicative of action potential duration in anesthetized animals,
- ECG parameters measured in conscious or anesthetized animals,
- Proarrhythmic effects measured in isolated cardiac preparations or animals.

As indicated above, these four functional levels can be investigated by *in vitro* and/or *in vivo* methods. Findings from the functional levels listed above are considered useful and complementary.

*In vitro* electrophysiology studies can explore potential cellular mechanisms that might not be evident from *in vivo* data. Changes in other cardiovascular parameters or effects on multiple ion channels can complicate interpretation of data. Complementary assessments in other systems can address this issue. Although delay of repolarization can occur through modulation of several types of ion channels, inhibition of  $I_{Kr}$  is the most common mechanism responsible for pharmaceutical-induced prolongation of QT interval in humans.

*In vivo* models that possess the full complement of molecular, biochemical, and physiological systems can also be informative with regard to the response in humans to the test substance. Carefully designed and conducted *in vivo* studies allow evaluation of parent substance and metabolites, and can enable estimation of safety margins. *In vivo* ECG evaluations provide information on conduction properties and non-cardiac influences (e.g., autonomic nervous system tone). Studies of action potential parameters provide information on the integrated activity of multiple ion channels in the heart.

## Non-clinical Testing Strategy



### 2.3 Non-clinical Testing Strategy

The following sections describe a general non-clinical testing strategy for assessing risk for delayed ventricular repolarization and QT interval prolongation that is pragmatic and based on currently available information. The figure illustrates the component elements of the testing strategy, but not specific test systems or their designs.

#### 2.3.1 *In vitro* $I_{Kr}$ assay

An *in vitro*  $I_{Kr}$  assay evaluates the effects on the ionic current through a native or expressed  $I_{Kr}$  channel protein, such as that encoded by hERG (see section 3.1.2).

### **2.3.2 *In vivo* QT assay**

An *in vivo* QT assay measures indices of ventricular repolarization such as QT interval (see section 3.1.3). This assay can be designed to meet the objective of both ICH S7A (cardiovascular core battery study) and S7B. This will reduce the use of animals and other resources.

### **2.3.3 Chemical/pharmacological class**

Consideration should be given to whether the test substance belongs to a chemical/pharmacological class in which some members have been shown to induce QT interval prolongation in humans (e.g., antipsychotics, histamine H-1 receptor antagonists, fluoroquinolones). This factor should, where appropriate, influence the choice of reference compound(s) and be included in the integrated risk assessment.

### **2.3.4 Relevant non-clinical and clinical information**

Additional information for the integrated risk assessment can include results from:

- Pharmacodynamic studies,
- Toxicology/safety studies,
- Pharmacokinetic studies, including plasma levels of parent substance and metabolites (including human data if available),
- Drug interaction studies,
- Tissue distribution and accumulation studies,
- Post-marketing surveillance.

### **2.3.5 Follow-up studies**

Follow-up studies are intended to provide greater depth of understanding or additional knowledge regarding the potential of test substance for delayed ventricular repolarization and QT interval prolongation in humans. Such studies can provide additional information concerning potency, mechanism of action, slope of the dose-response curve, or magnitude of the response. Follow-up studies are designed to address specific issues, and, as a result, various *in vivo* or *in vitro* study designs can be applicable.

In circumstances where results among non-clinical studies are inconsistent and/or results of clinical studies differ from those for non-clinical studies, retrospective evaluation and follow-up non-clinical studies can be used to understand the basis for the discrepancies. Results from follow-up studies can be a significant component of an integrated risk assessment.

Relevant non-clinical and clinical information along with the following should be considered in the selection and design of follow-up studies:

- Use of ventricular repolarization assays that measure action potential parameters in isolated cardiac preparations (see section 3.1.2),
- Use of specific electrophysiological parameters indicative of action potential duration in anesthetized animals (see section 3.1.3),
- Repeated administration of test substance,
- Selection of animal species and gender(s),
- Use of metabolic inducers or inhibitors,

- Use of concurrent positive control substances and reference compounds (see section 3.1.1),
- Inhibition of other channels not previously evaluated,
- Measurement of electrophysiological parameters at multiple time points,
- Confounding effects in conscious animals that limit the interpretation of data such as test substance-induced effects on heart rate or autonomic tone, or toxicities such as tremor, convulsion, or emesis.

### **2.3.6 Integrated risk assessment**

The integrated risk assessment is the evaluation of non-clinical study results including the results from follow-up studies and other relevant information. The integrated risk assessment should be scientifically based and individualized for the test substance. Such an assessment can contribute to the design of clinical investigations and interpretation of their results. When available, the integrated risk assessment should be included in the Investigator's Brochure and the Non-clinical Overview (ICH M4). Depending on the stage of drug development, the integrated risk assessment should also consider:

- Assay sensitivity and specificity,
- Potencies of test substance in S7B assays relative to reference compound(s),
- Relationship between the exposures associated with an effect on repolarization and those eliciting the primary pharmacodynamic effect in the non-clinical test species or the proposed therapeutic effect in humans,
- Contribution of metabolites to QT interval prolongation as well as metabolic differences between humans and animals.

### **2.3.7 Evidence of risk**

Evidence of risk is the overall conclusion from the integrated risk assessment for a test substance to delay ventricular repolarization and prolong QT interval in humans.

## **2.4 Timing of S7B Non-clinical Studies and Integrated Risk Assessment in Relation to Clinical Development**

Conduct of S7B non-clinical studies assessing the risk for delayed ventricular repolarization and QT interval prolongation prior to first administration in humans should be considered. These results, as part of an integrated risk assessment, can support the planning and interpretation of subsequent clinical studies.

## **3. TEST SYSTEMS**

### **3.1 Considerations for Test Systems**

This section provides an overview of methodologies currently used to assess the potential for a test substance to delay ventricular repolarization and to prolong QT interval. The following should be considered in selecting the most appropriate test systems:

- Assay methodology and experimental endpoints are scientifically valid and robust,
- Assays and preparations are standardized,
- Results are reproducible,
- Endpoints/parameters of the assays are relevant for assessing human risk.

### **3.1.1 Use of positive control substances and reference compounds**

A sub-maximally effective concentration of a positive control substance should be used to demonstrate the responsiveness of *in vitro* preparations for ion channel and action potential duration assays and should be included in every study. In the case of *in vivo* studies, positive control substances should be used to validate and define the sensitivity of the test system, but need not be included in every study.

For test substances belonging to a chemical/pharmacological class that is associated with QT interval prolongation in humans, the use of concurrent reference compound(s) (member(s) of the same class) in *in vitro* and *in vivo* studies should be considered to facilitate ranking the potency of the test substance in relation to its comparators.

### **3.1.2 *In vitro* electrophysiology studies**

*In vitro* electrophysiology studies can provide valuable information concerning the effect of a test substance on action potential duration and/or cardiac ionic currents. These assays have an important role in assessing the potential for QT interval prolongation and elucidating cellular mechanisms affecting repolarization. *In vitro* electrophysiology studies employ either single cell (e.g., heterologous expression systems, disaggregated cardiomyocytes) or multicellular (e.g., Purkinje fiber; papillary muscle; trabeculae; perfused myocardium; intact heart) preparations. Heterologous expression systems, where human ion channel protein(s) are expressed in noncardiac cell lines, are used to assess the effects of a test substance on a specific ion channel. Disaggregated myocytes are technically more challenging than the expression systems but have the advantage of being suitable for assessing effects on both action potential duration and ionic currents. Although single cell preparations are more fragile, they minimize diffusional barriers to the site of action. Multicellular preparations are stable test systems to study action potential duration. The analysis of parameters for each phase of the action potential such as  $V_{max}$  for phase 0 ( $I_{Na}$ ), APD<sub>30</sub> or APD<sub>40</sub> for phase 2 ( $I_{Ca}$ ) and “triangulation” for phase 3 ( $I_K$ ) can be useful to investigate the effects on specific channels responsible for these phases. In addition, some parameters derived from the Langendorff preparation have been reported to provide information regarding proarrhythmic risk.

Tissue and cell preparations for *in vitro* assays are obtained from different laboratory animal species including rabbit, ferret, guinea pig, dog, swine, and occasionally from humans. The ionic mechanisms of repolarization in adult rats and mice differ from larger species, including humans (the primary ion currents controlling repolarization in adult rats and mice is  $I_{to}$ ); therefore, use of tissues from these species is not considered appropriate. Species differences in terms of which cardiac ion channels contribute to cardiac repolarization and to the duration of the action potential should be considered in selecting a test system. When native cardiac tissues or cells are used, the characteristics and source of the preparation should be considered because the distribution of ion channel types varies according to the region and type of cell.

Test substance concentrations for *in vitro* studies should span a broad range, covering and exceeding the anticipated maximal therapeutic plasma concentration. Ascending concentrations should be tested until a concentration-response curve has been characterized or physicochemical effects become concentration-limiting. Ideally, the duration of exposure should be sufficient to obtain steady-state electrophysiological effects, unless precluded by the viability of the cell or tissue preparation. The duration of exposure should be indicated. Appropriate positive control substances should be used to establish the sensitivity of the *in vitro* assay system.

Factors that can confound or limit the interpretation of *in vitro* electrophysiology studies include the following:

- The testing of high concentrations of the test substance can be precluded by limited solubility in aqueous physiological salt solutions,
- Adsorption to glass or plastic or non-specific binding to the test matrix can reduce the concentration of the test substance in the incubation or perfusion medium,
- Test substance concentrations can be limited by cytotoxic or physicochemical attributes of the test substance that disrupt cell membrane integrity so that electrophysiological endpoints cannot be obtained,
- Cardiac cells and tissues have limited capacity for drug metabolism; therefore, *in vitro* studies using the parent substance do not provide information on the effects of metabolites. When *in vivo* non-clinical or clinical studies reveal QT interval prolongation that is not consistent with data from *in vitro* studies using the parent substance, testing metabolites in the *in vitro* test systems should be considered.

New technologies for potassium channel assays are being developed. Novel ion channel activity assays can be useful in preliminary screening of test substances to identify lead candidates. It is important to demonstrate concordance between conventional and new technologies before adopting new technologies for regulatory purposes.

Competition binding protocols, in which test substances are studied for their ability to displace a radiolabeled hERG channel blocker from a cell line expressing hERG, are used. However, competition for radioligand-binding sites provides no information on agonistic or antagonistic effects of the test substance on  $I_{Kr}$ . Moreover, this assay will not identify test substances that bind to hERG at sites other than the radioligand binding sites. Based upon these potential limitations, this assay is not considered a substitute for voltage clamp assays described above.

### **3.1.3 *In vivo* electrophysiology studies**

Intact animal models allow investigation of ventricular repolarization or associated arrhythmias where integrated effects on the full complement of ion channel and cell types are assessed. Also, potential neuronal and hormonal influences on the pharmacodynamic effect of the pharmaceuticals are present in animals.

The QT interval of the ECG is the most commonly used endpoint to gauge effects of a test substance on ventricular repolarization. In specialized electrophysiology studies, information regarding the ventricular repolarization (e.g., monophasic action potential duration and effective refractory period) can also be obtained from *in vivo* models. Additional safety parameters of interest, including blood pressure, heart rate, PR interval, QRS duration, and arrhythmias, can be assessed simultaneously.

The QT interval and heart rate have an inverse, non-linear relationship, which varies among species and between animals within a species. Thus, a change in heart rate exerts an effect on QT interval, which can confound the assessment of the effect of the test substance on ventricular repolarization and the QT interval. There are two important situations where there is variability in heart rate among animals: one is due to difference in autonomic tone, and the other is due to effects of test substances on heart rate. Therefore, the interpretation of data from *in vivo* test systems should take into account the effect of coincident changes in heart rate. Ideally, QT interval data obtained after administration of a test substance should be compared with control and baseline data at similar heart rates. When the heart rate variability is not due to the test substance, it can be reduced by acclimatization, or the use of anesthetized animal models. When the effects are due to a test substance, the most common approach is to

correct the QT interval for heart rate (QTc) using formulae such as Bazett or Fridericia. The choice of heart rate correction formula should be justified with data from the test system. When differences in heart rate between treatment and control are large, the correction formulae may not be effective for assessing risk of QT interval prolongation. An alternative approach is to maintain a constant heart rate using cardiac pacing. An analysis of QT/RR relationship, including correction of the QT interval using formulae for individual animals, may be more appropriate.

Laboratory animal species used for *in vivo* electrophysiology studies include dog, monkey, swine, rabbit, ferret, and guinea pig. The ionic mechanisms of repolarization in adult rats and mice differ from larger species, including humans (the primary ion currents controlling repolarization in adult rats and mice is  $I_{to}$ ); therefore, use of these species is not considered appropriate. The most appropriate *in vivo* test systems and species should be selected and justified.

The dose range should be in accord with that discussed in ICH S7A and, whenever feasible, should include and exceed the anticipated human exposure. The dose range can be limited by animal intolerance to the test substance, e.g., emesis, tremor, or hyperactivity. For studies designed to relate the extent of delayed ventricular repolarization to concentrations of the parent test substance and its metabolites, controlled exposure via constant intravenous infusion can be used. Monitoring exposure to the test substance and metabolites (see ICH S3A) provides opportunities to interpret dose- and concentration-response data and to design follow-up studies, if appropriate.

Factors that should be considered in conducting studies and interpreting the results include the following:

- Data acquisition and analysis methods,
- Sensitivity and reproducibility of the test systems,
- Dosing period and measurement points,
- Heart rate and other effects that confound interpretation of QT interval data,
- Inter-species and gender differences, e.g., cardiac electrophysiology, hemodynamics, or metabolism of pharmaceuticals,
- Pharmaceuticals that have effects on several ion channels can yield complex dose-response relationships that could be difficult to interpret.

### **3.1.4 Simulated pathological conditions and arrhythmias**

The precise relationship between test substance-induced delay of ventricular repolarization and risk of proarrhythmia is not known. Directly assessing the proarrhythmic risk of pharmaceuticals that prolong the QT interval would be a logical undertaking. Indices of proarrhythmic activity (e.g., electrical instability, temporal and/or spatial dispersion of refractoriness, reverse use-dependency, changes in action potential configuration) and animal models might have utility in assessing proarrhythmia. Interested parties are encouraged to develop these models and test their usefulness in predicting risk in humans.