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Disease characterization using LQTS-specific induced pluripotent stem cells

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Aims Long QT syndrome (LQTS) is an inheritable and life-threatening disease; however, it is often difficult to determine disease characteristics in sporadic cases with novel mutations, and more precise analysis is necessary for the successful development of evidence-based clinical therapies. This study thus sought to better characterize ion channel cardiac disorders using induced pluripotent stem cells (iPSCs).

Methods and results We reprogrammed somatic cells from a patient with sporadic LQTS and from controls, and differentiated them into cardiomyocytes through embryoid body (EB) formation. Electrophysiological analysis of the LQTS-iPSC-derived EBs using a multi-electrode array (MEA) system revealed a markedly prolonged field potential duration (FPD). The IKr blocker E4031 significantly prolonged FPD in control- and LQTS-iPSC-derived EBs and induced frequent severe arrhythmia only in LQTS-iPSC-derived EBs. The IKs blocker chromanol 293B did not prolong FPD in the LQTS-iPSC-derived EBs, but significantly prolonged FPD in the control EBs, suggesting the involvement of IKs disturbance in the patient. Patch-clamp analysis and immunostaining confirmed a dominant-negative role for 1893delC in IKs channels due to a trafficking deficiency in iPSC-derived cardiomyocytes and human embryonic kidney (HEK) cells.

Conclusions This study demonstrated that iPSCs could be useful to characterize LQTS disease as well as drug responses in the LQTS patient with a novel mutation. Such analyses may in turn lead to future progress in personalized medicine.

Keywords Long QT syndrome • Drug examination • iPS cells • Cardiomyocytes • Personalized medicine

1. Introduction

Sudden cardiac arrest (SCA) is a major cause of mortality in developed countries, accounting for about 10% of all deaths.[1] The majority of sudden cardiac deaths are caused by acute ventricular tachyarrhythmias,[2] which often occur in persons without known cardiac disease, structural heart disease, or coronary artery disease.[3–6] Long QT syndrome (LQTS) was initially described as a rare inherited disease causing ventricular tachyarrhythmia. Subsequently, many patients have been identified and now we know that ventricular tachyarrhythmia in LQTS is apparently common among sudden death syndromes. The reported incidence of LQTS is one in 2000, but this may underestimate the disease because many cases are not properly diagnosed because of the rarity of the condition and the wide spectrum of symptoms.[7]

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Human-induced pluripotent stem cells (hiPSCs) have become a promising tool for analysing human genetic diseases.[8,9] Many studies have already shown that apparent cellular phenotypes of familial genetic disorders are recapitulated by disease-specific iPSC-derived cells *in vitro*. In some of these, cardiomyocytes differentiated from LQTS-specific iPSCs (LQTS-iPSCs) were used to recapitulate disease phenotypes in LQTS patients who were previously characterized as having mutated channel profiles.[10–13] In reality, many patients have novel mutations and no such specific information regarding their disease phenotype is matched by the respective genotypes. To address whether iPSC technology could be used to characterize a novel mutated gene, we selected LQTS patients without family history and previous disease characterization.

2. Methods

2.1 Human iPSC generation

iPSCs were established as described previously.[8] We used lentiviral to introduce mouse solute carrier family 7, a member 1 (*Slc7a1*) gene encoding the ecotropic retrovirus receptor. Transfectants were plated at 2×10^5 cells per 60 mm dish. The next day, *OCT3/4*, *SOX2*, *KLF4*, and *c-MYC* were introduced by retroviral. Twenty four hours after transduction, aspirated off the virus-containing medium, then continued to culture under fibroblast condition. Six days later, the cells were harvested and plated at 5×10^4 cells per 100 mm dish. The cells were cultured for another 20 days. At day 25, embryonic stem cell-like colonies were mechanically dissociated and transferred to a 24-well plate on the mouse embryonic fibroblast feeders.

2.2 Patient consent

All subjects provided informed consent for blood testing for genetic abnormalities associated with hereditary LQTS. Isolation and use of patient and control fibroblasts was approved by the Ethics Committee of Keio University (20-92-5), and performed only after written consent was obtained. Our study also conforms with the principles outlined in the Declaration of Helsinki for use of human tissue or subjects.[14]

2.3 *In vitro* differentiation

Cells were harvested using 1 mg/ml collagenase IV (Invitrogen, CA, USA), and transferred to ultra-low attachment plates (Corning, NY, USA) in differentiation medium.[15] The medium was replaced every second day. The time window of differentiation for analysing the beating embryoid bodies (EBs) and cardiomyocytes was 30–60 days and 150 days from starting the differentiating conditions.

2.4 Immunofluorescence

The immunostaining was performed using the following primary antibodies and reagents: anti-OCT3/4 (sc-5279, Santa Cruz, CA, USA), anti-E-cadherin (M108, TAKARA BIO, Otsu, Japan), anti-NANOG (RCAB0003P, ReproCELL, Yokohama, Japan), anti-SSEA 1(sc-21702, Santa Cruz), anti-SSEA 3 (MAB4303, Millipore, MA, USA), anti-SSEA 4 (MAB4304, Millipore), anti-Tra1-60 (MAB4360, Millipore), anti-Tra1-81 (MAB4381, Millipore), anti-α-Actinin (A7811, Sigma-Aldrich, MO, USA), anti-ANP (sc-20158, Santa Cruz), anti-MHC (MF20, Developmental Studies Hybridoma Bank, IA, USA), anti-TNNT (13-11, Thermo Scientific, NeoMarkers, MA, USA), anti-GATA4 (sc-1237, Santa Cruz), anti-NKX2.5 (sc-8697, Santa Cruz), anti-KCNQ1 (s37A-10, ab84819, Abcam, Cambridgeshire, UK), anti-WT-KCNQ1 (APC-022, Alomone Labs, Jerusalem, Israel), fluorescent phallotoxins (A22283, Molecular Probes, OR, USA), Wheat Germ Agglutinin Conjugates[16,17] (W11262, Molecular Probes) and DAPI (Molecular Probes). Signal was detected using a conventional fluorescence laser microscope (BZ-9000, KEYENCE, Osaka, Japan) equipped with a colour charge-coupled device camera (BZ-9000, KEYENCE).

2.5 Reverse transcription–polymerase chain reaction

Total RNA samples were isolated using the TRIZOL reagent (Invitrogen) and RNase-free DNase I (Qiagen, Tokyo, Japan). cDNAs were synthesized using the Superscript First-Strand Synthesis System (Invitrogen). Real-time quantitative reverse transcription–polymerase chain reaction (RT–PCR) was performed using 7500 Real-Time PCR System (Applied Biosystems, CA, USA), with SYBR Premix ExTaq (Takara, Otsu, Japan). The amount of mRNA was normalized to GAPDH mRNA. Primer sequences are listed in the Supplementary material online, *Table*.

2.6 Teratoma formation

The mice were anaesthetized using a mixture of ketamine (50 mg/kg), xylazine (10 mg/kg), and chlorpromazine (1.25 mg/kg). The adequacy of anaesthesia was monitored by heart rate, muscle relaxation, and the loss of sensory reflex response, i.e. non-response to tail pinching. hiPSCs (at a concentration corresponding to 25% of the cells from a confluent 150 mm dish) were injected into the testis of severe combined immunodeficiency disease (SCID) mice (CREA Japan, Tokyo, Japan). At 6–8 weeks post-injection, teratomas were dissected, fixed in 10% paraformaldehyde overnight, and embedded in paraffin. The sections were stained with haematoxylin and eosin. All experiments were performed in accordance with the Keio University animal care guidelines and approved by the Ethics Committee of Keio University (20-041-4), which conforms to the Guide for the Care and Use of Laboratory Animals published by the US National Institutes of Health (NIH Publication no. 85-23, revised 1996).

2.7 Karyotype analysis

Karyotype analysis was performed using standard Q-banding chromosome analysis according to the Central Institute for Experimental Animals.

2.8 Genomic sequence

Genomic DNA was isolated from the patient, control volunteers, control iPSC colonies, and LQTS-iPSC colonies. The relevant *KNCQ1* gene fragment was amplified by PCR reaction using 100 ng genomic DNA. PCR products were then sequenced.

2.9 Cell culture and transient transfection

Human embryonic kidney (HEK) cells were obtained from the American Type Cell Collection and seeded in 35 mm dishes 1 day before transfection and then transfected with various plasmids using FuGENE 6 Transfection Reagent (Roche Applied Science, Penzberg, Germany). Aliquots of 1 or 0.5 μg of WT-*KCNQ1* and/or 1 or 0.5 μg of P631fs/33-*KCNQ1*, together with 1 μg of WT-*KCNE1* and 0.2 μg of GFP, were transfected into HEK cells. Cells were studied at 48–72 h after transfection.

2.10 Field potential recordings using the on-chip multi-electrode array system

Multi-electrode array (MEA) chips from Multi Channel Systems (Germany) were coated with fibronectin (F1141; Sigma-Aldrich). EBs were plated and incubated at 37°C. MEA measurements were performed at 37°C. The signals were initially processed, and the obtained data were subsequently analysed with MC_Rack (Multi Channel Systems). Data for analysis were extracted from 2–5 min of the obtained data. The recorded extracellular electrograms were used to determine local field potential duration (FPD), defined as the time interval between the initial deflection of the FP and the maximum local T wave. FPD measurements were normalized (corrected FPD: cFPD) to the activation rate using Bazett's correction formulae: $cFPD = FPD/(RR\ interval)^{1/2}$, where RR indicates the time interval (in seconds) between two consecutive beats.[18] E4031

(M5060; Sigma-Aldrich), chromanol 293B (C2615; Sigma-Aldrich), barium chloride (Fluka 34252; Sigma-Aldrich), isoproterenol hydrochloride (I6504; Sigma-Aldrich), and propranolol hydrochloride (P0884; Sigma-Aldrich) were prepared as 1 or 10 mM stock solutions. The FPs were recorded for 5 min. Drug was then added to the medium. After 5–10 min of incubation, the FPs were measured for 5–10 min. MEA recordings were performed by investigators blinded to the genotype of the cells.

2.11 Whole-cell patch-clamp electrophysiology

The external solution used to measure K^+ currents in iPSC-derived cardiomyocytes was composed of the following (in mM): *N*-methyl-D-glucamine 149, $MgCl_2$ 5, HEPES 5, and nisoldipine 0.003. IKs were separated by applying chromanol 293B. In HEK cells, Tyrode's solution used to measure KCNQ1 channel currents comprised (in mM): NaCl 143, KCl 5.4, $CaCl_2$ 1.8, $MgCl_2$ 0.5, NaH_2PO_4 0.25, HEPES 5.0, and glucose 5.6; pH was adjusted to 7.4 with NaOH. The glass pipette had a resistance of 3–5 MΩ after filling with the internal pipette solution containing (in mM) KOH 60, KCl 80, aspartate 40, HEPES 5, EGTA 10, Mg ATP 5, sodium creatinine phosphate 5, and $CaCl_2$ 0.65; pH 7.2. KCNQ1 channel currents were recorded using Axopatch 200B, Digidata 1440A, and pClamp 10.2 (Axon Instruments, Foster City, CA, USA) for data amplification, acquisition, and analysis, respectively. For K^+ current measurement in iPSC-derived cardiomyocytes, depolarizing pulses for 3 s from −60 to 60 mV were applied from the holding potential at −60 mV at 0.1 Hz. The tail current was measured on repolarization back to −40 mV. KCNQ1 channel currents were elicited by 3 s depolarizing steps from a holding potential of −80 mV to potentials ranging from −50 to +60 mV in 10 mV increments. This was followed by a 2 s repolarization phase to −40 mV to elicit the tail current. Pulse frequency was 0.1 Hz. Whole-cell patch-clamp recordings were performed by investigators blinded to the genotype of the cells.

2.12 Statistical analysis

Data are expressed as mean ± SEM. Unless otherwise noted, statistical significance was assessed with Student's *t*-test and Fischer's exact test for simple comparisons, and ANOVA followed by Bonferroni's test for multiple comparisons. The probability level accepted for significance was $P < 0.05$ ($^*P < 0.05$, $^{**}P < 0.01$).

3. Results

A 13-year-old boy was admitted to our institution with SCA experienced during physical exercise at school. He subsequently underwent successful resuscitation using an automated external defibrillator , the data from which showed ventricular fibrillation, a fatal arrhythmic event (see Supplementary material online, *Figure S1A*). Electrocardiogram showed a significantly prolonged QT interval and QT interval corrected for heart rate, QTc (see Supplementary material online, *Figure S1B*). He had no family history of previous syncope episodes or significant QT interval abnormality (see Supplementary material online, *Figure S1C*). Since the clinical findings on syncope and the electrocardiogram morphology suggested type 1 LQTS, β-blockers were initially administered to reduce the risk of cardiac sudden death.[19] The epinephrine provocation test increases the accuracy of diagnosis of type 1 LQTS;[20] however, this test can be affected by β-blocker administration (see Supplementary material online, *Figure S1D*); thus, type 1 LQTS being the most probable diagnosis in our patient was not definitive.[21] To elucidate whether this patient is type 1 LQTS caused by a *KCNQ1* mutation, *KCNQ1* was directly sequenced. A heterozygous deletion mutant in *KCNQ1*, 1893delC (P631fs/33), was identified in our patient (see Supplementary material online, *Figure S1E* and *F*). We also confirmed that no other mutation was present in the major LQTS-related genes: *KCNH2*, *SCN5A*, *KCNE1*, and *KCNE2*. Although the *KCNQ1* 1893delC mutation was previously reported, its functional characteristics remain unknown.[22] To obtain electrophysiological properties, drug responses, and some valid data on which to base useful medical therapy, we tested the validity of iPSCs for disease characterization.

To generate iPSCs, we used dermal fibroblasts from our patient and two healthy volunteers, and reprogrammed these cells using retrovirus-mediated gene transfer of *SOX2*, *OCT3/4* (also known as *POU5F1*), *KLF4*, and *MYC*. Several clones were generated, expanded, and stored. All iPSC lines showed typical iPSC morphology and expressed human pluripotency markers (*Figure 1A* and *B*). Quantitative RT–PCR (qRT–PCR) analyses confirmed that all lines adequately expressed endogenous pluripotency markers and silenced exogenous genes (*Figure 1C* and *D*). To examine pluripotency, iPSCs were injected into SCID mice. Injected iPSC-derived teratomas contained the cell derivatives of all three germ layers, such as cartilage, intestine, muscle, and neural tissue (see Supplementary material online, *Figure S2A* and *B*). All iPSC lines maintained a normal karyotype (see Supplementary material online, *Figure S2C* and *D*). We selected two LQTS and two control iPSC lines for further characterization and cardiac differentiation.

We used an EB culture system to differentiate iPSCs into cardiomyocytes.[15,23] After 1 week of floating culture, spontaneous beating EBs were observed, and the efficiency of beating EBs showed no significant difference between control- and LQTS-iPSCs at days 30 and 60 (data not shown). Immunofluorescence staining for dissociated cardiomyocytes showed clear immunopositivity for cardiac-specific gene products in control- and LQTS-iPSC-derived cardiomyocytes (*Figure 2A* and *B*). Electron microscopy also revealed a typical cardiomyocyte structure in both control- and LQTS-iPSC-derived cardiomyocytes, including sarcomeric organization and gap junctions (see Supplementary material online, *Figure S3A* and *B*). Similarly, qRT–PCR analyses confirmed the expression of cardiac-specific genes and ion channels (*Figure 2C*). Ion channel expression in iPSCs was compatible with previous reports of multiple ion channels expressed in pluripotent stem cells.[24,25] To elucidate electrophysiological properties, we used an MEA system that enables easy measurement of the surface electrogenic activities of cell clusters and can be adapted to automatic high-throughput systems.[26] MEA analyses revealed that control- and LQTS-iPSC-derived EBs showed similar rhythmic electrical activity and spontaneous beating rate (*Figure 3A* and *B*). FPD in MEA analysis is analogous to a QT interval in an electrocardiogram.[26] The cFPD (normalized to beating frequency) of LQTS-iPSC-derived EBs was significantly longer than that of controls (*Figure 3C* and *D*), suggesting that iPSC-derived cardiomyocytes from both control and LQTS cells have cardiac-specific functional properties.

We next tested several drugs known to affect QT prolongation to elucidate the electrophysiological properties of EBs. The IKr blocker, E4031, significantly prolonged cFPD in a dose-dependent manner when added into the culture medium of control and LQTS cells (*Figure 4A* and *B*). E4031 administration induced significantly more frequent early-after depolarizations (EADs) in the LQTS-iPSC-derived beating EBs compared with the control EBs; these are spontaneous membrane depolarizations that confer risk of ventricular arrhythmias (*Figure 4C* and Supplementary material online, *Figure S4A*). In addition, higher doses of E4031 induced arrhythmic events such as

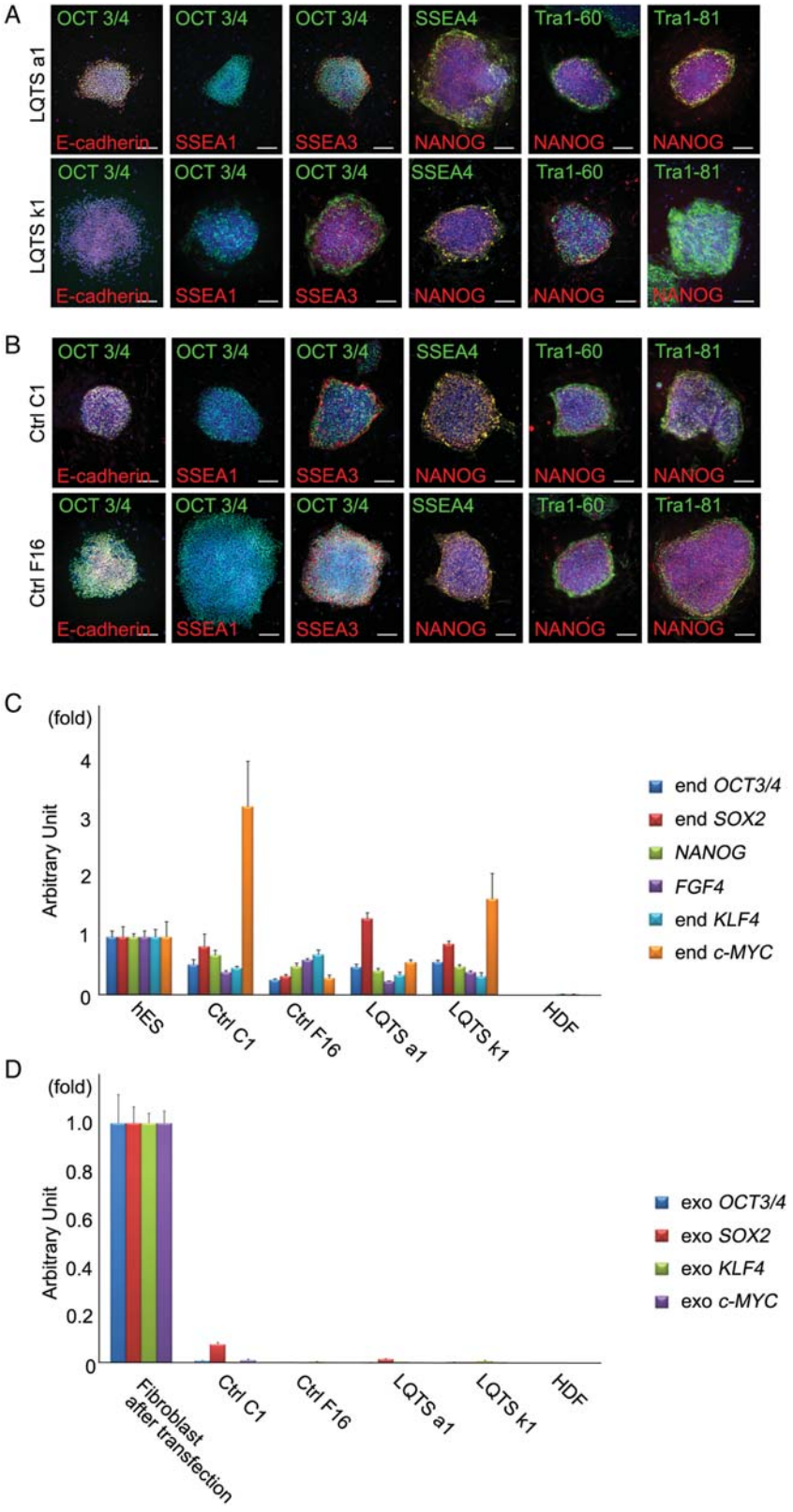

Figure 1 Generation of iPSCs from a patient with LQTS. (*A*) Immunofluorescence staining for stem cell markers (OCT3/4, E-cadherin, NANOG, SSEA3, SSEA4, Tra1-60 and Tra1-81) in LQTS-iPSC colonies. SSEA1 is not a stem cell marker in hiPSCs. Scale bar, 100 μm. (*B*) Immunofluorescence staining for stem cell markers in control-iPSC colonies. Scale bar, 100 μm. (*C*) Quantitative RT–PCR analyses for endogenous *OCT3/4*, endogenous *Sox2*, endogenous *KLF4*, endogenous *c-MYC*, and *NANOG* and *FGF4* in hES, control-iPSC, LQTS-iPSC, and human dermal fibroblasts (HDF). (*D*) Quantitative RT–PCR analyses for exogenous *OCT3/4*, exogenous *Sox2*, exogenous *KLF4* and exogenous *c-MYC* in HDF at 6 days after transfection, control-iPSC, LQTS-iPSC, and HDF.

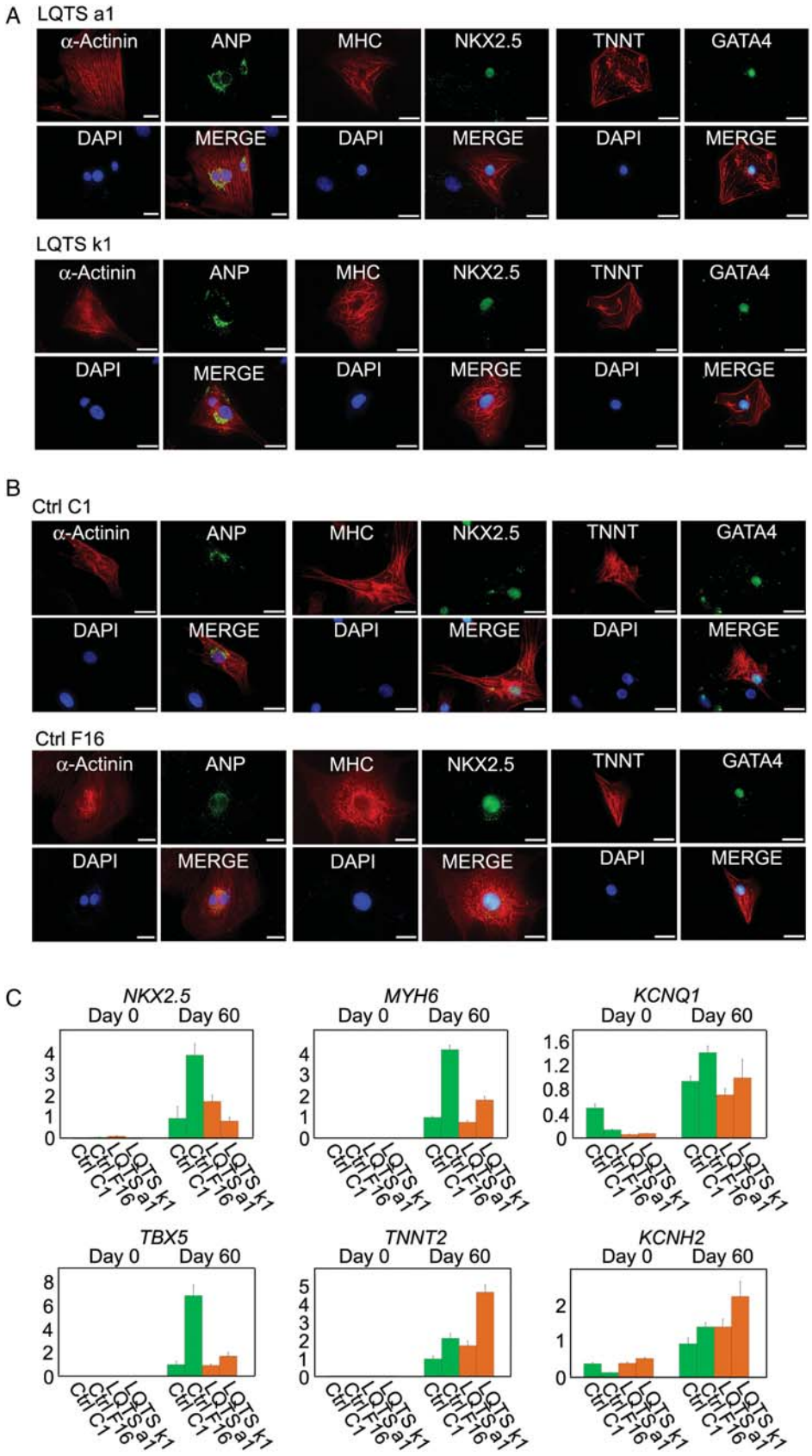

Figure 2 Cardiomyocyte generation from control- and LQTS-iPSCs. (*A*) and (*B*) Immunofluorescence staining for cardiac markers (α-Actinin, ANP, MHC, NKX2.5, GATA4, and TNNT) in the LQTS- and control-iPSC-derived cardiomyocytes. Scale bar, 20 μm. (*C*) Quantitative RT–PCR analyses for cardiac markers (*NKX2.5*, *TBX5*, *MYH6*, and *TNNT2*) and ion channels (*KCNQ1* and *KCNH2*) in the control- (Ctrl) and LQTS-iPSC, and in iPS-derived EBs at day 60.

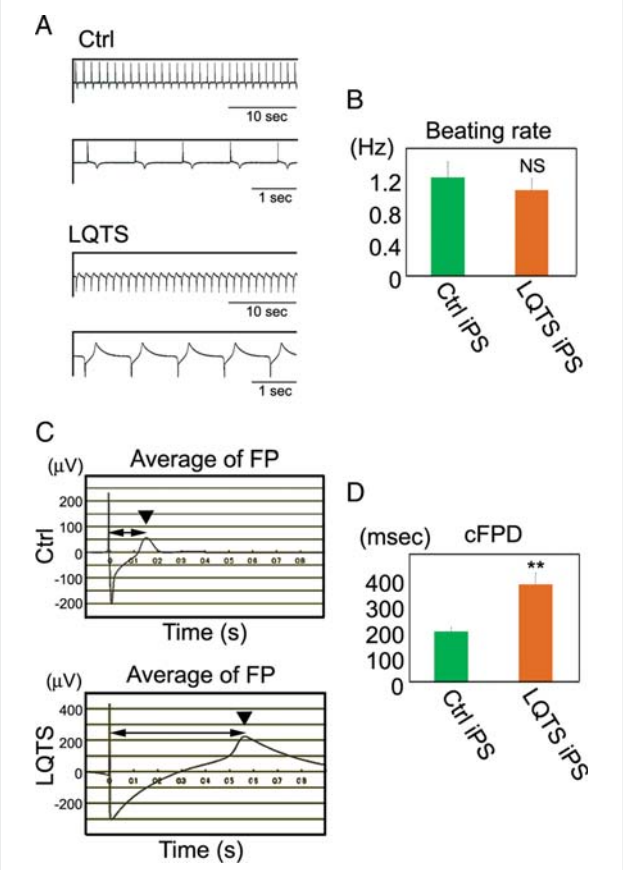

Figure 3 Electrophysiological features of LQTS-iPSC-derived cardiomyocytes. (*A*) Representative MEA recording from the control- and LQTS-iPSC-derived beating EBs. (*B*) Beating rate of the control- and LQTS-iPSC-derived EBs. (*C*) Average of field potential (FP) recorded by MEA in the control- ($n = 12$) and LQTS-iPSC-derived beating EBs ($n = 12$). Triangle indicates the peak of FP and bilateral arrow indicates the FPD. (*D*) cFPD obtained from the control- ($n = 12$) and LQTS-iPSC-derived beating EBs ($n = 12$).

polymorphic ventricular tachycardia (PVT)-like arrhythmia (*Figure 4D* and Supplementary material online, *Figure S4A*).[27] E4031-induced PVT-like arrhythmias were never observed in control-iPSC-derived beating EBs. We then found that another major repolarization potassium current relating to LQTS, IKs, was blocked by chromanol 293B, which significantly prolonged cFPD in control-iPSC-derived beating EBs, but not in LQTS-iPSC-derived beating EBs (*Figure 4E* and *F*). These data indicated that LQTS-iPSC-derived cardiomyocytes have IKs channel dysfunction and/or chromanol 293B insensitivity. We also examined the inwardly rectifying potassium current IK1 by the IK1-blocking barium administration. The application of barium prolonged FPD in both control- and LQTS-iPSC-derived cardiomyocytes (see Supplementary material online, *Figure S4B*). However, barium administration did not induce arrhythmogenic events in control- and LQTS-iPSC-derived beating EBs. These findings suggested that repolarization of LQTS-iPSC-derived cardiomyocytes would be mainly controlled by IKr. Taken together with IKr and IKs blocker administration, we proposed that IKs channels were not only genetically but functionally impaired and that IKr channels compensated for this effect in the patient-derived iPSCs, which is also known as the repolarization reserve in cardiomyocytes.[28,29] IKs channel impairment is diagnosed as type 1 LQTS. And it is well known that β-stimulant increases the risk of fatal arrhythmia and that β-blockers would effectively prevent long-QT-related arrhythmia in type1 LQTS.[30] The β-stimulant isoproterenol increased the beating rate in a dose-dependent manner in control and LQTS cells, and induced EAD and ventricular tachycardia (VT)-like arrhythmogenic events in LQTS-iPSC-derived beating EBs (see Supplementary material online, *Figure S5A* and *B* and *Figure 4G*). Interestingly, the non-selective β-blocker propranolol obviously decreased the incidence of arrhythmogenic events (*Figure 4H*). These data strongly suggested that our patient has a functional impairment in the IKs channel system. We confirmed a heterozygous deletion mutant in KCNQ1, 1893delC (P631fs/33), was identified in the LQTS-iPSCs (see Supplementary material online, *Figure S5C*).

To confirm a possible dominant-negative role of the *KCNQ1* 1893delC mutation in IKs channel function, we conducted precise electrophysiological characterizations in iPSC-derived cardiomyocytes. IKs currents can be recorded by subtraction of baseline and the IKs blocker (chromanol 293B) addition. In control, chromanol 293B (30 μM) addition apparently decreased the recorded current, and IKs current was recorded by subtraction (*Figure 5A*). In LQTS-derived cardiomyocytes, chromanol 293B addition did not show apparent differences and IKs current was subtly recorded by subtraction (*Figure 5A*). The IKs peak and tail current densities of the LQTS-derived cardiomyocytes were evidently smaller than those of control (*Figure 5B*). To clarify the mechanisms underlying such effects, we examined KCNQ1 protein expression in LQTS-iPSC-derived cardiomyocytes. We conducted immunofluorescent staining using an antibody that recognizes a C-terminal epitope on *KCNQ1* downstream of P631fs/33. Immunostaining in control showed cell peripheral expression of KCNQ1, which suggested normal shuttling of the KCNQ1 protein into the cell membrane (*Figure 5C*). In LQTS-iPSC-derived cardiomyocytes, the KCNQ1 protein was accumulated at the perinuclear cytoplasm and nucleus, instead of at the cell periphery (*Figure 5C*). These data indicated that KCNQ1 expression is downregulated at the membrane peripheral site (*Figure 5D*), which suggests that KCNQ1 1893delC has a dominant-negative effect via a trafficking deficiency.

We showed this patient has a mutation in *KCNQ1* and that LQTS-iPSC-derived cardiomyocytes have a functional disturbance in KCNQ1 channels. However, it remains unclear whether this mutation directly contributed and whether other mutations could be involved in the IKs current disturbance. To test for a pure dominant-negative role of the *KCNQ1* 1893delC mutation in IKs channel function, we also conducted electrophysiological and histochemical characterizations in HEK cells expressing exogenous wild-type and/or mutated KCNQ1. Cells with 100% incorporation of the wild-type *KCNQ1* (WT) gene recorded typical IKs currents and 50% WT *KCNQ1* gene introduction slightly reduced the IKs currents (*Figure 6A*). Introduction of 100% mutant *KNCQ1* genes (P631fs/33) (MT) significantly reduced IKs currents (*Figure 6A*). Moreover, 50% WT and 50% MT gene introductions had dominant-negative effects on IKs current (*Figure 6A*). The IKs peak and tail current densities of the 100% MT and 50/50% WT and MT were evidently smaller than those of 100% WT and 50% WT (*Figure 6B* and *C*). Then we also examined KCNQ1 protein expression in *KCNQ1*-transfected HEK cells. Cells

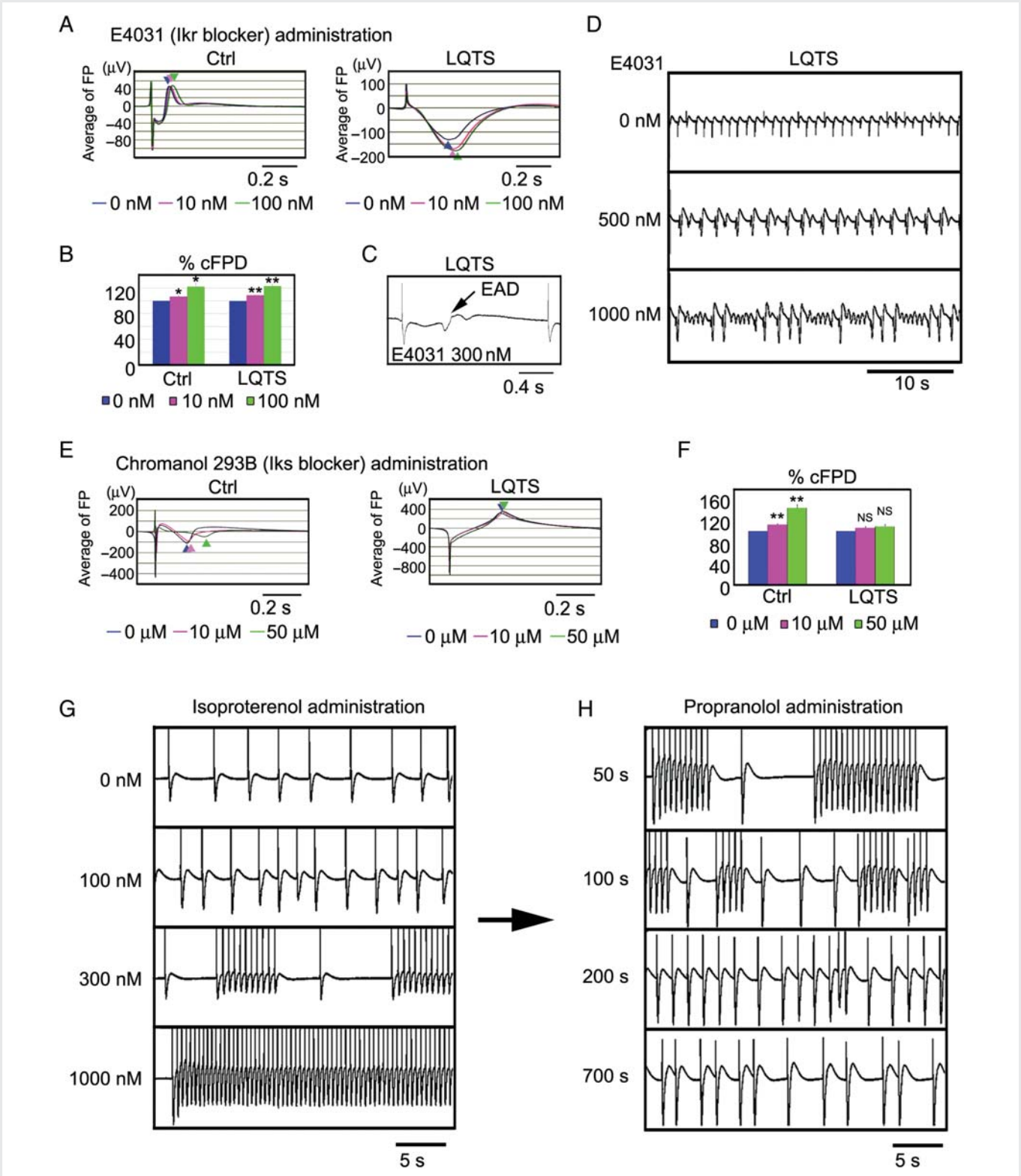

Figure 4 Drug responses of LQTS-iPSC-derived cardiomyocytes. (*A*) Average of FP recorded by MEA after E4031 administration in the control- and LQTS-iPSC-derived beating EBs. Triangle indicates the peak of FP. (*B*) Per cent change of cFPD after E4031 administration obtained from the control- ($n = 6$) and LQTS-iPSC-derived beating EBs ($n = 6$). (*C*) Representative MEA recordings showing EAD after E4031 administration in LQTS-iPSC-derived beating EBs. The frequency of appearing EAD in each cell is control- ($n = 1/16$) and LQTS-iPSC-derived beating EBs ($n = 8/16$). (*D*) Representative MEA records showing PVT-like arrhythmia after E4031 administration in LQTS-iPSC-derived beating EBs. (*E*) Average of FP recorded by MEA after chromanol 293B administration in the control- and LQTS-iPSC-derived beating EBs. Triangle indicates the peak of FP. (*F*) Per cent change of cFPD after chromanol 293B administration obtained from the control- ($n = 8$) and LQTS-iPSC-derived beating EBs ($n = 8$). (*G*) Representative MEA records showing VT-like arrhythmia after isoproterenol administration in LQTS-iPSC-derived beating EBs. (*H*) MEA recordings after propranolol (2 μM) administration in LQTS-iPSC-derived beating EBs during isoproterenol-induced VT-like arrhythmia.

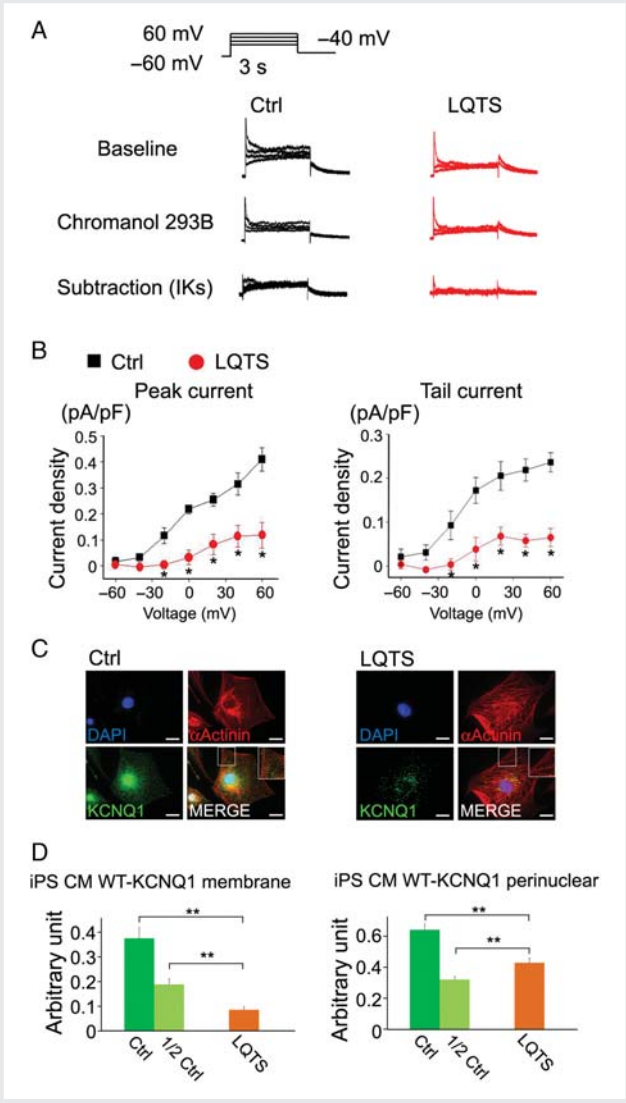

Figure 5 Dominant-negative role of the *KCNQ1* 1893delC mutant in iPSC-derived cardiomyocytes. (*A*) The pulse protocol is shown in the upper panel. Representative current traces of baseline, chromanol 293B (30 μM) administration and subtraction expressed in control- and LQTS-iPSC-derived cardiomyocytes. (*B*) In the left panel, current–voltage relationship of peak current during the test depolarization pulse in control- and LQTS-iPSC-derived cardiomyocytes. In the right panel, current–voltage relationship of tail current upon repolarization to −40 mV following test depolarization in control- ($n = 7$) and LQTS-iPSC-derived cardiomyocytes ($n = 7$). (*C*) Immunofluorescence staining for KCNQ1 and α-Actinin staining in control- and LQTS-iPSC-derived cardiomyocytes. White boxes in each figure are shown at a higher magnification in the inset. Scale bar, 20 μm. (*D*) Densitometric analyses for WT-KCNQ1 expression at membrane peripheral and perinuclear sites in control- ($n = 20$) and LQTS-iPSC-derived cardiomyocytes (CM) ($n = 20$).

carrying 100% WT and 50% WT gene introduction showed cell peripheral expression of KCNQ1, which suggested normal shuttling of the KCNQ1 protein into the cell membrane (*Figure 6D* and *E* and Supplementary material online, *Figure S6*). In contrast, 100% MT and 50/50% WT and MT gene introduction induced KCNQ1 protein accumulation around the perinuclear cytoplasm, instead of at the cell periphery (*Figure 6D* and *E* and Supplementary material online, *Figure S6*). These data indicated that MT-KCNQ1 expression is down-regulated at the membrane peripheral site, which suggests that *KCNQ1* 1893delC has a dominant-negative effect via a trafficking deficiency.

4. Discussion

Human iPSCs have become a promising tool to analyse genetic diseases. Some previous reports indicated that disease-specific iPSCs recapitulated the disease phenotypes.[10–13] However, most patients for generating iPSCs in previous reports were already diagnosed with responsible genes and/or had familial history.[10–13,31,32] We showed here that iPSCs can recapitulate the phenotype of a sporadic patient with LQTS type1. We also performed functional analysis of the novel mutation by using patient-specific iPSCs, which may support the diagnosis of LQTS type 1 with novel mutation. Moreover, using this system allowed us to perform several drug administration tests on the iPSC-derived cardiomyocytes, which would be a realistic risk to such a patient in real medical practice. Patients with LQTS type 1 have to take β-blockers throughout their lives, and thus to confirm that β-blockers truly prevent arrhythmic events in the patients with novel mutations, patient-specific iPSC-derived cardiomyocytes could also be used for drug evaluation and monitoring.

We generated iPSCs from a sporadic LQTS patient with a novel heterozygous mutation located in the *KCNQ1* gene, 1893delC, and differentiated into cardiomyocytes. The electrophysiological function was measured by the MEA system, and we confirmed that cFPD was markedly prolonged in LQTS, as compared with control. Next, we tried to confirm the responsible channel for disease phenotype by precise examination of several drug responses. IKr is responsible for the main potassium current in cardiomyocytes and the IKr blocker significantly prolonged cFPD in LQTS- and control-iPSC-derived beating EBs. But interestingly, we observed more frequently the arrhythmogenic events like EAD in LQTS-derived beating EBs, and PVT-like arrhythmia findings recorded only in LQTS. In addition, IKs is another important potassium current in cardiomyocytes but the IKs blocker did not affect cFPD in LQTS, though it significantly prolonged control's cFPD in a dose-dependent manner. In general, IKr and IKs channels work in a complementary fashion in cardiomyocytes, which is known as repolarization reserve.[28,29,33] Taken together with IKr and IKs administration, we could propose that IKs channels were functionally impaired and that IKr channels would compensate for this effect in the patient-derived iPSCs. It was also supported that the diagnosis of our patient may be LQTS type1 because of the onset of the ventricular fibrillation caused by exertional stress.[20,21] It is important to elucidate whether the disease phenotype is reproducible in the same clinical situation, but it should be better to avoid reproducing ventricular fibrillation in those patients because of the high risk of sudden death. Therefore, we examined whether adrenergic stimulation can cause arrhythmogenic events in LQTS-iPSCs-derived cardiomyocytes. We successfully reproduced that the β-stimulant, isoproterenol, induced VT-like arrhythmia only in LQTS, which was totally blocked by the β-blocker, propranolol. These findings strongly suggested that patient's IKs channels were functionally impaired and we focused on the identification of the responsible gene mutation in the *KCNQ1* gene. To confirm the dominant-negative role of the *KCNQ1* 1893delC mutation in IKs channel function, we examined electrophysiological and histochemical analyses in iPSC-derived

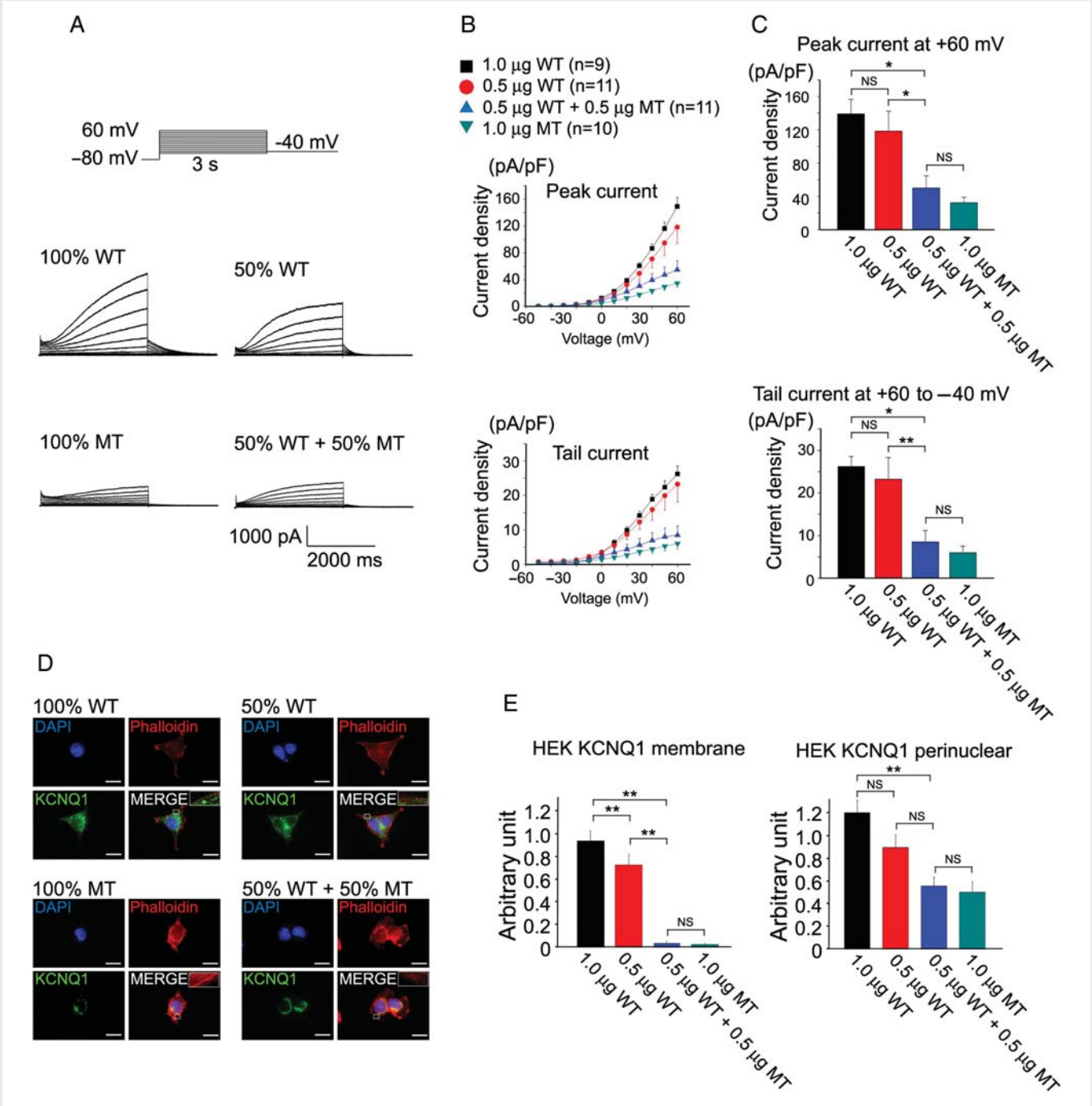

Figure 6 Dominant-negative role of the *KCNQ1* 1893delC mutant in HEK cells. (*A*) The pulse protocol is shown in the upper left panel. Representative current traces of WT- and/or P631fs/33-KCNQ1 expressed in HEK cells. Cells of each panel were transfected as follows: 100% WT-KCNQ1, 50% WT-KCNQ1, 50% WT + 50% P631fs/33-KCNQ1, and 100% P631fs/33-KCNQ1. (*B*) In the upper panel, current–voltage relationship of peak current during the test depolarization pulse in HEK cells introduced with 100% WT, 50% WT, 100% MT, and 50% WT + 50% MT *KCNQ1* genes. In the lower panel, current–voltage relationship of tail current upon repolarization to −40 mV following test depolarization in HEK cells introduced with 100% WT, 50% WT, 100% MT, and 50% WT + 50% MT *KCNQ1* genes. (*C*) Summary of the peak and tail current densities measured following the test depolarization pulse of +60 mV. In the upper panel, bar graphs showing current densities of developing (peak) recorded current at +60 mV. In the lower panel, bar graphs showing current densities of tail current recorded upon repolarization to −40 mV from +60 mV test depolarization. (*D*) Immunofluorescence staining for KCNQ1 and phalloidin staining in HEK cells introduced with 100% WT, 50% WT, 100% MT, and 50% WT + 50% MT *KCNQ1* genes. White boxes in each figure are shown at higher magnifications in the inset. Scale bar, 20 µm. (*E*) Densitometric analyses for KCNQ1 expression at membrane peripheral and perinuclear sites in HEK cells introduced with 100% WT ($n = 14$), 50% WT ($n = 15$), 100% MT ($n = 14$), and 50% WT + 50% MT *KCNQ1* genes ($n = 13$).

cardiomyocytes, and showed that *KCNQ1* 1893delC has a dominant-negative effect via a trafficking deficiency. And there remains a possibility that other mutated genes might be involved in disease phenotypes. So we examined electrophysiological and histochemical analyses in HEK cells in which WT and MT *KCNQ1* genes were transferred, and showed that *KCNQ1* 1893delC has a dominant-negative effect via a trafficking deficiency.

This study had several limitations with respect to basic research and clinical application. In our study, the control subjects were two healthy volunteers who were unrelated to the patient. The type of such controls that are optimal to use in disease modelling using patient-specific iPSCs remains under discussion.[34] To examine pure functions of the mutated genes, it would seem better to compare patient's family members who do not harbour the mutation, although related family members share genetic information including single nucleotide polymorphisms, and this could affect disease phenotypes. A recent study also showed that ideal control iPSCs can be obtained by mutated gene correction using a targeting strategy.[35] However, it is sometimes difficult to establish iPSCs from family members and correct a mutated gene in human iPSCs. In our study, we used control iPSCs from healthy unrelated volunteers and also performed functional analysis of the mutated genes using gene transduction. Another important issue for routine clinical application of disease modelling using iPSCs is the time path. It takes a few months to generate iPSCs from the patient's dermal fibroblasts, and another few months to differentiate iPSCs into cardiac myocytes. Thus, a minimum of half of year is required to generate iPSC-derived cardiomyocytes that reproduce the patient's phenotype. Although iPSC technology is an attractive tool for analysing human diseases, it is clear that technological innovation remains necessary for the use of iPSCs in routine medical practice.

In the present study, we showed that patient-derived iPSCs could recapitulate disease phenotype in a case of sporadic LQTS. Importantly, this study demonstrated that iPSCs could be useful to characterize the electrophysiological cellular phenotype of a patient with a novel mutation. In terms of effort, cost, and time, such a method for characterizing a phenotype should overcome several problems that remain in realizing the routine clinical application potential of patient-derived iPSC technology, and in turn, the promise of personalized medicine in the future clinical setting.

Supplementary material

Supplementary material is available at *Cardiovascular Research* online.

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