The hyperpolarization-activated cyclic nucleotide-gated (HCN) cation (Na+/K+) currents (If/Ih) are generated by 4 members of the channel family (HCN1–4).¹ These currents contribute to the pacemaker function² in heart and brain.³ The HCN4 current is known to play a crucial role in the automaticity of the sinus node through the generation of a slow diastolic depolarization during the phase 4 of the cardiac action potential.⁴ Thus, it is a crucial channel for appropriate pacemaker activity and conduction system function because it facilitates rapid repolarization. Interestingly, HCN4 has been shown to be expressed in essentially the entire heart tissue.⁵ Mutations in HCN4 have been associated mainly with sick sinus syndrome phenotype⁶; however, in recent years, a broad spectrum of phenotypes has been reported, including sinus bradycardia,⁷ inappropriate sinus tachycardia,⁸ early-onset atrial fibrillation,⁹,¹⁰ atrioventricular block,¹¹,¹² idiopathic ventricular tachycardia,¹³ left ventricular noncompaction (LVNC),¹⁴–¹⁷ dilation of the aorta, and mood and anxiety disorders.¹⁹ In the present study, we report a case with sick sinus syndrome, LVNC, mood and anxiety disorders, and ventricular fibrillation (VF) hosting 2 novel HCN4-pore mutations.

CASE REPORT

The index patient was a 36-year-old man, who presented initially with mood and anxiety disorders characterized by important depressive episodes. Previous clinical records revealed a slightly impaired left ventricular function, paroxysmal atrial fibrillation, frequent premature ventricular complexes, and nonsustained tachycardia originating from the right ventricle. Therapy with β-blocker was initiated but discontinued shortly because of profound sinus bradycardia, which did not resume after washout. A cardiac magnetic resonance imaging excluded a right ventricular cardiomyopathy. The left ventricle showed an uncommon hypertrabeculation; however, the criteria for an LVNC were not fulfilled at that time.

Eight years later, the patient was hospitalized because of heart failure and rapid conducted atrial fibrillation. At this time, he exhibited a severely depressed left ventricular function with left ventricular end-diastolic diameter of 62 mm, reduced right ventricular function (tricuspid annular plane systolic excursion of 8 mm) and biventricular apical hypertrabeculation more pronounced in the left side. With a β-blocker and amiodarone, spontaneous conversion to sinus rhythm occurred, but marked sinus bradycardia was noted, despite reduction of β-blocker and amiodarone doses (Figure 1A). While hospitalized, he presented frequent premature ventricular complexes and VF with the need of resuscitation (Figure 1B).

Reversible causes for VF were excluded, the resting electrocardiogram exhibited sinus bradycardia and left anterior fascicular block (Figure 1C). The echocardiography after recompensation of heart failure was diagnostic for LVNC²⁰,²¹ and showed an improved biventricular function (Figure 1D). A dual-chamber internal cardioverter defibrillator was implanted, and a dual chamber with rate response stimulation at
90 beats per minute with a long atrio-ventricular delay to avoid ventricular stimulation successfully prevented further ventricular arrhythmias. After 2 months, the stimulation rate was reduced to 70 beats per minute.

The patient’s arrhythmic and LVNC phenotype at relatively young age raised a suspicion for a possible underlying inherited arrhythmogenic condition; therefore, genetic testing and familial evaluation were recommended. Because of patient’s limited contact with all first-degree relatives, cardiac evaluation was only possible in 1 brother who was asymptomatic. The mother had a pacemaker implanted at 47 years of age and died 15 years later because of coronary heart disease; no tissue was available. The father died at 86 years of age, from an unknown cause.

METHODS
Subjects
The data, analytic methods, and study materials will not be made available to other researchers for purposes of reproducing the results or replicating the procedure because of patient confidentiality policy.

This study was conducted in full agreement with the principles of the Declaration of Helsinki and laws and regulations of Switzerland. All DNA donors available for this study signed an informed consent form approved by the local ethical committee.

Figure 1. Electrocardiogram and echocardiographic characteristics of the proband.
A, Persistent sinus bradycardia after conversion from atrial fibrillation, despite low dose of β-blocker. Top to Bottom, simultaneous recording of ECG lead II, oxygen saturation wave, ECG lead V₃, and respiratory wave. B, Premature ventricular complexes triggering nonsustained ventricular tachycardia, followed by ventricular fibrillation with the need of resuscitation and external defibrillation (not shown). Top to Bottom, simultaneous recording of ECG lead II, PLETH (plethysmograph, oxygen saturation wave, disconnected), ECG lead V₃, and ECG lead aVR. C, 12-lead ECG at rest, showing sinus bradycardia, left anterior fascicular block, and isodiasic T waves from V₂ through V₆. D, Four-chamber view echocardiogram after heart failure recompensation consistent with the diagnosis of left ventricular noncompaction cardiomyopathy (1. thickened myocardium with a noncompacted inner layer and compacted outer layer; 2. thickness ratio of noncompacted-to-compacted myocardium, >2; 3. typical predominant localization apical, midlateral, and midinferior; and 4. thickness of the compacted myocardium, <8.1 mm). ECG indicates electrocardiogram.

Molecular Genetic Analysis
DNA was extracted from peripheral blood using standard procedures. Candidate gene sequencing was performed using the TruSight One Sequencing Panel (Illumina, San Diego, CA), containing 4813 genes associated with known clinical phenotypes. One hundred ninety-three genes previously associated with cardiac diseases were analyzed. Read alignment and local realignment of indels were performed using CLC Workbench v7.5.1 (Qiagen, Redwood City, CA). We used a number of different databases (HGMD Professional; Qiagen, Redwood City, CA) and published original literature to identify known disease-causing mutations in the datasets from the patients. Novel, putative disease-associated sequence variants were distinguished from polymorphisms using the following filtering criteria: a change in the protein’s primary structure, species conservation of the underlying amino acid, and an allele frequency <1% based on the 1000 Genome Project database. For detailed sequence analysis and interpretation of sequence variations, we used the following bioinformatic algorithms and
Functional Assay

Human embryonic kidney (HEK)-293 cells were cultured in Dulbecco modified Eagle medium (Euroclone, Milan, and Italy) supplemented with 10% fetal bovine serum (Euroclone, Milan, and Italy), 1% Pen Strep (100 U/mL of penicillin and 100 μg/mL of streptomycin), and stored in a 37°C humidified incubator with 5% CO₂. HEK-293 cells were transiently transfected with WT (wild type) or mutant human HCN4 cDNA (codon-optimized synthesis using the Gene Art service by Thermo Fisher Scientific, Waltham, MA) using Turbofect transfection reagent (Thermo Fisher, Waltham, MA) according to the manufacturer’s recommended protocol. For each 35-mm Petri dish, 1 μg or 0.5 μg of the HCN4-containing vector (pcDNA3.1) and 0.3 μg of green fluorescent protein (GFP)-containing plasmid (pmaxGFP; AmaxaBiosystems, Gaithersburg, MD) were used. In heteromeric studies, the amount of each HCN4 plasmid was 0.5 μg per Petri dish. In the control cell, 1.3 μg of GFP-containing plasmid was used for the transfection. Thirty to 72 hours after the transfection, the cells were dispersed by trypsin treatment. Green fluorescent cells were selected for patch-clamp experiments at room temperature (≈25°C). Currents were recorded in whole cell configuration with a Dagan 3900A (Degan, Minneapolis, MN); data were digitized with an Axon Digidata 1322 A/D (Axon Instruments, CA) converter and analyzed off-line with Axon pClamp9. Patch pipettes were fabricated from 1.5 mm outer diameter borosilicate glass capillaries with a P-97 Flaming/Brown Micropipette Puller (Sutter, Novato, CA) and had resistances of 3 to 5 MΩ.

RESULTS

Two novel mutations in the HCN4 gene were found in the proband: c.1454C>A p.(Ala485Glu) and c.1435A>G p.(Ile479Val). Both variants were present in the same Next Generation Sequencing reads suggesting that they were in cis c.(1454C>A; 1435A>G). They both localized to the pore region of the HCN4 channel and were predicted to be pathogenic by SIFT, Polyphen2, Mutation Taster, and were absent in HGMDB, 1000 Genomes, and Exome Aggregation Consortium Browser encompassing >60000 sequenced exomes. The patient’s brother did not carry any of the 2 HCN4 mutations. No tissue was available from the parents for genetic examination.

Transfected HEK-293 cells transiently expressing the WT and the mutant channels were subjected to electrophysiological measurements, example currents were obtained from cells transfected with 1 μg of HCN4 plasmid, whereas cells transfected with only GFP plasmid served as a control. (Figure 2A and 2B). WT channels produced the typical time- and voltage-dependent inward currents that result in the current/voltage relationship and activation curve (Figure 2C and 2D). By fitting the Boltzmann equation to the activation curve (Figure 2D), we obtained a half-activation value of −103.1±0.2 mV and a slope factor k=11±0.2 mV. These values are consistent with published data on HCN4²⁸ functionally expressed in HEK-293 cells. Notably, transfection of 1 μg of the single mutants (I479V and A485E), as well as of the double mutant (I479V/A485E), did not generate any measurable HCN4-like current (Figure 2A). The small current of these cells is indistinguishable from that of the control cells, transfected with GFP only (Figure 2A and current/voltage relationship in Figure 2C).

When the double mutant was cotransfected with the WT channel (0.5 μg each plasmid), cells exhibited typical HCN4-like currents (Figure 2B). A detailed analysis showed that the voltage dependence (Figure 2D) of these currents and their activation kinetics (Figure 2E) were identical to that of the WT channel expressed alone. Only the amplitude of these currents was reduced by a factor of 2 (Figure 2C), suggesting that the decrease in current level was solely reflecting the reduced amount of WT plasmid in these experiments. The finding that WT channels, when coexpressed with...
the mutants, show WT-like currents underscores the notion that the mutants have no dominant-negative effect on functional channel.

**DISCUSSION**

**HCN4** gene mutations were described initially in patients with sick sinus syndrome. In recent years, it has become evident that additional phenotypes can be caused by mutations in **HCN4**. LVNC is one of the phenotypes described in recent years. In particular, the pore mutation p.Gly482Arg has been described several times in association with LVNC. Here, we described another case with LVNC and 2 pore mutations in cis, close to the well-known **HCN4**-Gly482Arg mutation. We, therefore, hypothesize that this region represents a hot spot for the LVNC phenotype. We also observed a VF phenotype, not described before in **HCN4** muta-
CONCLUSIONS

HCN4 mutations confer diverse phenotypes, characterized by the previously described bradycardia, sick sinus syndrome, LVNC, mood and anxiety disorders, and susceptibility to VF as described here. Our study clearly suggests that the HCN4-I479V/A485E mutant phenotype can be explained by a lower number of active channels rather than altered current properties. Collectively, the data suggest that the mutation reflects the situation of a partial knockout of the HCN4 channel.

REFERENCES


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DISCLOSURES

None.

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