

Mutation Analysis of Candidate Genes *SCN1B*, *KCND3* and *ANK2* in Patients with Clinical Diagnosis of Long QT Syndrome

M. RAUDENSKÁ¹, A. BITTNEROVÁ², T. NOVOTNÝ³, A. FLORIÁNOVÁ³,
K. CHROUST¹, R. GAILLYOVÁ², B. SEMRÁD³, J. KADLECOVÁ², M. ŠIŠÁKOVÁ³,
O. TOMAN³, J. ŠPINAR³

¹Department of Genetics and Molecular Biology, Faculty of Science, Masaryk University, Brno,
²Department of Medical Genetics, University Hospital Brno, Brno, ³Department of Internal
Medicine and Cardiology, University Hospital Brno, Brno, Czech Republic

Received December 27, 2006

Accepted August 6, 2007

On-line November 30, 2007

Summary

The long QT syndrome (LQTS) is a monogenic disorder characterized by prolongation of the QT interval on electrocardiogram and syncope or sudden death caused by polymorphic ventricular tachycardia (torsades de pointes). In general, mutations in cardiac ion channel genes (*KCNQ1*, *KCNH2*, *SCN5A*, *KCNE1*, *KCNE2*) have been identified as a cause for LQTS. About 50-60 % of LQTS patients have an identifiable LQTS causing mutation in one of mentioned genes. In a group of 12 LQTS patients with no identified mutations in these genes we have tested a hypothesis that other candidate genes could be involved in LQTS pathophysiology. *SCN1B* and *KCND3* genes encode ion channel proteins, *ANK2* gene encodes cytoskeletal protein interacting with ion channels. To screen coding regions of genes *SCN1B*, *KCND3*, and 10 exons of *ANK2* following methods were used: PCR, SSCP, and DNA sequencing. Five polymorphisms were found in screened candidate genes, 2 polymorphisms in *KCND3* and 3 in *SCN1B*. None of found polymorphisms has coding effect nor is located close to splice sites or has any similarity to known splicing enhancer motifs. Polymorphism G246T in *SCN1B* is a novel one. No mutation directly causing LQTS was found. Molecular mechanism of LQTS genesis in these patients remains unclear.

Key words

ANK2 • Candidate genes • KCND3 • Long QT syndrome • SCN1B

Corresponding author

T. Novotný, Department of Internal Medicine and Cardiology,
University Hospital Brno Bohunice, Jihlavská 20, 625 00 Brno,
Czech Republic. E-mail: tnovotny@fnbrno.cz

Introduction

The long QT syndrome (LQTS) is a monogenic disorder characterized by prolongation of the QT interval on electrocardiogram and syncope or sudden death caused by polymorphic ventricular tachycardia (torsades de pointes).

In general, mutations in cardiac ion channel genes (*KCNQ1*, *KCNH2*, *SCN5A*, *KCNE1*, *KCNE2*) have been identified as a cause for LQTS (Splawski *et al.* 2000). Recently, mutation in cytoskeletal protein gene *ANK2* has also been linked to LQTS in one French family (Mohler *et al.* 2003, 2004). About 50-60 % of LQTS patients have an identifiable LQTS-causing mutation in one of the 5 most prevalent cardiac channel genes (Tester *et al.* 2005). In the others the disease mechanism remains unclear. The aim of this study is to test the hypothesis that other cardiac ion channel genes could be involved in LQTS pathophysiology: *SCN1B* gene encodes $\beta 1$ subunit of cardiac Na^+ channel and plays an important role in channel inactivation (Wallace *et al.* 2002). *KCND3* is a gene that encodes the K^+ channel that underlies the potassium transient outward current I_{to} in the human ventricle (Dixon *et al.* 1996). Targeted mutational analysis of *ANK2* was also completed.

Methods

Group of patients

The group of patients was recruited from

Table 1. Clinical characteristics of study subjects.

Patient	Age	Sex	QTc (ms)	Syncope	Torsades de pointes	LQTS in family	Diagnostic score (points)
IB	64	F	0.48	0	0	+	4
MK	62	F	0.5	+	+	+	7
MI	42	F	0.48	+	0	+	5
LP	13	M	0.47	0	0	+	3
MZ	25	F	0.5	+	0	+	5
MK	25	M	0.47	+	0	+	4
PD	25	F	0.5	+	0	0	4
MD	58	F	0.54	+	+	0	6
JJ	46	M	0.47	0	0	+	3
AL	20	F	0.49	+	0	0	4
MS	16	F	0.48	+	+	0	5
ŠK	17	F	0.48	+	0	+	5

Sex: M – male, F – female, QTc – QT interval corrected to heart rate according to Bazett formula ($QTc=QT/RR^{1/2}$), diagnostic scoring: 2-3 points – intermediate probability of LQTS, ≥ 4 points – high probability of LQTS.

25 unrelated individuals who were consecutively referred to the Department of Internal Medicine and Cardiology with suspicion on LQTS. They were examined clinically including bicycle ergometry. In all of them intermediate or high probability of LQTS was present based on diagnostic score (Schwartz *et al.* 1993). In this scoring system various point values are assigned to various symptoms, a value of 2-3 indicates intermediate probability and ≥ 4 points indicates high probability of LQTS diagnosis.

Informed consent was obtained from all the individuals and peripheral blood samples were taken. Mutational analysis of *KCNQ1*, *KCNH2*, *SCN5A*, *KCNE1* and *KCNE2* genes was performed by methods published elsewhere (Splawski *et al.* 2000). In 11 patients the *KCNQ1* gene mutations and in 2 patients the *KCNH2* gene mutations were present. In the other 12 patients no mutation in the above mentioned LQTS related genes was found. These 12 individuals were subjects of this study – mutational analysis was extended to following genes: *SCN1B*, *KCND3* and exons 36-37 and 39-46 of *ANK2*. The brain-specific exon 38 was not analyzed in this study. Clinical characteristics of study subjects are summarized in Table 1.

Genomic DNA Extraction and PCR

Genomic DNA was extracted from samples of peripheral blood according to the standard protocol using DNA BloodSpin Kit and the standard chloroform/ethanol

method. Eleven oligonucleotide primer pairs were used to amplify coding area of *KCND3*, as proposed by Postma *et al.* (2000), only the fifth segment of the first coding exon had different reverse primer (GGT CAT CCA GCT GCC CTC CAA CCT), which agrees with sequence of *KCND3* in NCBI database (accession number NT 019273). Ten primer pairs were disposed to amplify chosen exons of *ANK2* (from 36 to 46 except 38). These primers were taken from Mohler *et al.* (2003). For the PCR amplification of *SCN1B* gene coding and UTR region were suggested primers using Primer3 (Rozen and Skaletsky 2000), (Table 2). Sequences of these primers agree with sequence of *SCN1B* in Ensembl database (© 2006 WTSI / EBI, ENSG00000105711).

SSCP analysis

For the analysis of *KCND3* and *ANK2* 3 μ l aliquots of the amplified sample were mixed with 5 μ l of bromphenol blue loading dye, for analysis of *SCN1B* 1 μ l aliquots of the amplified sample were mixed with 3 μ l of bromphenol blue loading dye and 6 μ l of destilated water. Samples were subsequently denatured by heating at 94 °C for 5 min, and placed into cold water to avoid renaturation. Then the samples were loaded on 9 % (*KCND3*), 11 % (*ANK2*) and 10 % (*SCN1B*) non-denaturing PAA gel. Electrophoresis was performed at 200 V and 10 °C for 3 h (*KCND3* and *ANK2*) and at 120 V and 18 °C for 12 h (all exons of *SCN1B* except exon 3). Exon 3 was performed at 10 °C.

Table 2. Oligonucleotide primers for detection of mutations in *SCN1B*.

Exon	Size, bp	Forward Primer Sequence	Reverse Primer Sequence
1.1	250 bp	5'-GGTGCACCTAGCGGATGT-3'	5'-TATTAATAGCGGGGCGAGAG-3'
1.2	284 bp	5'-GCTCCCGGGGACATTCTA-3'	5'-AACTTCTGAAGCTGACTTGG-3'
2	186 bp	5'-CTGTCCCCACAGTGCCT-3'	5'-CGCACACCTTGACAAACT-3'
3	266 bp	5'-CTGGCTACCCCTAGATCCT-3'	5'-ACCCGACTCACCTTTGTC-3'
4	200 bp	5'-CTGGGCTACCCCTTAACC-3'	5'-ACCTCCAGCCACCCTACT-3'
5	196 bp	5'-GGTCTGATGATGGGGTCACT-3'	5'-GCAAGAGAGGGGAATTAGG-3'
6.1	267 bp	5'-CCTAATCCCCCTCTCTTGC-3'	5'-AGCGGCAGTATTGCTTTACC-3'
6.2	289 bp	5'-CACTTTCGCCTCCTCCAG-3'	5'-CGGAGTGGGTCCCAGAAC-3'
6.3	275 bp	5'-GATGATGGGCTGGAGCAG-3'	5'-GGGGCTACAATCGAAACTA-3'

Table 3. Single nucleotide polymorphisms in *SCN1B*, *KCND3* and *ANK2* genes.

Patient	<i>SCN1B</i>	<i>KCND3</i>	<i>ANK2</i>
I	non	non	non
II	non	C264T/non	non
III	IVS+15 G>T/non = G246T/non	non	non
IV	IVS+15 G>T/non = G246T/non	C264T/non	non
V	non	non	non
VI	non	non	non
VII	non	C264T/C264T	non
VIII	non	non	non
IX	non	G669C/non	non
X	non	non	non
XI	T9204C/T9204C, A9248C/A9248C	non	non
XII	non	non	non

DNA sequencing

Genomic DNA obtained from 12 unrelated LQTS patients was screened for mutations in the coding regions of the genes *SCN1B*, *KCND3* and a part of the gene *ANK2* using SSCP analysis. If we have found three or four single strand bands in the SSCP patterns then we have done sequencing with forward and reverse sequencing primers. For purification of the amplified samples MinElute PCR Purification Kit (QIAGEN) was used. For cycle sequencing we used Big Dye Terminator Kit (Applied Biosystems) and for purification of samples after cycle sequencing DyeEx2.0 Spin Kit (Qiagen). Exons were sequenced by instrument ABI PRISM 310 (Applied Biosystems, USA).

Results

The result of the mutation screening is listed in the Table 3. None of found SNPs led to amino acid

changes, were located close to splice sites or had any similarity to known splicing enhancer motifs.

Discussion

About 50-60 % of LQTS patients have an identifiable LQTS-causing mutation in one of the five most prevalent cardiac channel genes. In the others the pathophysiology remains unknown. Possible mechanisms include involvement of other ion channels but also regulatory and other proteins. Recently, possible link to LQTS was found in several new genes: *KCNJ2* mutations in Andersen-Tawil syndrome (Tawil *et al.* 1994, Plaster *et al.* 2001), *CACNA1c* mutation in Timothy syndrome (Splawski *et al.* 2005), *CAV3* and *SCN4B* mutations in some LQTS patients (Vatta *et al.* 2006, Medeiros-Domingo *et al.* 2007). These are either rare complex neurological disorders (prolonged QT interval being not the leading symptom) or there are only anecdotal cases.

Thus it is still discussed if these diseases should be included among LQTS.

In this study we tested the hypothesis of other ion channels involvement. Three candidate genes were chosen for mutational analysis in 12 patients with clinical diagnosis of LQTS. *KCND3* encodes the K⁺ channel that underlies the potassium transient outward current I_{to} in the human ventricle (Dixon *et al.* 1996). I_{to} is especially important during the early phase of repolarization, as it sets the plateau voltage of both action potential (Tseng 1999).

In contrast to other genes, *ANK2* does not encode an ion channel but encodes a structural protein called ankyrin B that is most likely implicated in ion channels anchoring to the cellular membrane. A clue to the basis of this variant emerged from a study by Chauhan *et al.* (2000), in which sodium channel activity was altered in mice lacking ankyrin B – not an ion channel protein, but an adaptor protein that associated with cytoskeletal interactions. In this study, the ankyrin B spectrin-binding domain encoded by exons 36 and 37 of *ANK2* and the entire C-terminal domain encoded by exons 39-46 were screened. The brain-specific exon 38 and membrane-binding domain were not analyzed in this study.

SCN1B encodes the voltage-gated Na⁺-channel β 1 subunit (SCN1B). *SCN1B* is expressed in brain, skeletal muscle and heart. The α subunit alone can display functional channel properties, but requires the β subunits to modulate Na⁺-channel inactivation. Mutations in Na⁺-channel genes are known to cause paroxysmal excitability phenomena in skeletal muscle (myotonia, periodic paralysis) and heart (long QT syndrome) (Wallace *et al.* 2002). In the mutation database (Stenson *et al.* 2003) only one mutation in the SCN1B gene has been published. It is the substitution mutation C387G (on protein level C121W). This mutation causes a disruption of disulfide bridge and may alter the secondary structure of the extracellular domain (Wallace *et al.* 2002).

In our study, two allelic variants were found in *KCND3*. All variants were single nucleotide polymorphisms (SNPs) in coding regions. None of the coding SNPs led to amino acid changes, was located close to splice sites or had any similarity to known splicing enhancer motifs (Liu *et al.* 1998). All SNPs in *KCND3* were described in normal population too (Frank-Hansen *et al.* 2005). We assume that all the changes

detected in the LQTS patients were normal variants.

No allelic variant has been found in *ANK2* gene. Three allelic variants (all SNPs) were found in *SCN1B* gene, two of them T9204C and A9248C were detected previously (Ensembl database, © 2006 WTSI / EBI, ID:ENSG00000105711), G246T has not been published yet. By the help of ESEfinder Release 2.0 (Cartegni *et al.* 2003) we have found that G246T and T9204C substitution does not have any influence on DNA splicing. The substitution A9248C causes loss of one binding place for SC35 and SRp40 splicing proteins.

The fact that no mutations have been found, can have several reasons. The SSCP methodology can detect 88 and 90 % of mutations (Fodde and Losekoot 1994) and therefore we can not fully exclude the presence of mutations within analyzed genes in these individuals. The SSCP method is sensitive for the detection of point mutations or small deletions, but it can possibly miss large deletions. The SSCP method is the most widely used screening method because of its relative simplicity and low costs. Compared to more advanced methods, such as TmHPLC (Temperature Modulated High-Performance Liquid Chromatography) the SSCP has relatively low sensitivity.

LQTS causing mutations could also present in such regions of ion channel genes which are usually not examined. Alternatively, intronic mutations or mutation in the promoter and regulatory regions could be responsible for the disease symptoms. The possibility of other than ion channel genes being involved in the etiology of the long QT syndrome should not be refused, because of huge genetic heterogeneity of this disorder (see the above mentioned genes with recently discovered possible link to QT interval prolongation). This heterogeneity makes genetic testing much more difficult than in case if a single gene were responsible for the disease.

Molecular mechanism of LQTS genesis in our group of patients remains unclear.

Conflict of Interest

There is no conflict of interest.

Acknowledgements

The study was supported by Internal Grant Agency of Ministry of Health of the Czech Republic IGA MH NR/8063-3.

References

- CARTEGNI L, WANG J, ZHU Z, ZHANG M, KRAINER AR: ESEfinder: a web resource to identify exonic splicing enhancers. *Nucleic Acids Res* **31**: 3568-3571, 2003.
- CHAUHAN VS, TUVIA S, BUHUSI M, BENNETT V, GRANT AO: Abnormal cardiac Na⁺ channel properties and QT heart rate adaptation in neonatal ankyrin (B) knockout mice. *Circ Res* **86**: 441-447, 2000.
- DIXON JE, SHI W, WANG HS, McDONALD C, YU H, WYMORE R.S, COHEN IS, MCKINNON D: Role of the Kv4.3 K⁺ channel in ventricular muscle: a molecular correlate for the transient outward current. *Circ Res* **79**: 659-668, 1996.
- FODDE R, LOSEKOOT M: Mutation detection by denaturing gradient gel electrophoresis (DGGE). *Hum Mutat* **3**: 83-94, 1994.
- FRANK-HANSEN R, LARSEN LA, ANDERSEN P, JESPERGAARD C, CHRISTIANSEN M: Mutations in the genes KCND2 and KCND3 encoding the ion channels Kv4.2 and Kv4.3, conducting the cardiac fast transient outward current (I_{TO,f}), are not a frequent cause of long QT syndrome. *Clin Chim Acta* **351**: 95-100, 2005.
- LIU HX, ZHANG M, KRAINER AR: Identification of functional exonic splicing enhancer motifs recognized by individual SR proteins. *Genes Dev* **12**: 1998-2012, 1998.
- MEDEIROS-DOMINGO A, KAKU T, TESTER DJ, ITURRALDE-TORRES P, ITTY A, YE B, VALDIVIA C, UEDA K, CANIZALES-QUINTEROS S, TUSIE-LUNA MT, MAKIELSKI JC, ACKERMAN MJ: SCN4B-encoded sodium channel beta4 subunit in congenital long-QT syndrome. *Circulation* **116**: 134-142, 2007.
- MOHLER PJ, SCHOTT JJ, GRAMOLINI AO, DILLY KW, GUATIMOSIM S, DUBELL WH, SONG LS, HAUROGNE K, KYNDT F, ALI ME, ROGERS TB, LEDERER WJ, ESCANDE D, LEMARC H, BENNETT V: Ankyrin-B mutation causes type 4 long-QT cardiac arrhythmia and sudden cardiac death. *Nature* **421**: 634-639, 2003.
- MOHLER PJ, SPLAWSKI I, NAPOLITANO C, BOTTELLI G, SHARPE L, TIMOTHY K, PRIORI SG, KEATING MT, BENNETT V: A cardiac arrhythmia syndrome caused by loss of ankyrin-B function. *Proc Natl Acad Sci USA* **101**: 9137-9142, 2004.
- PLASTER NM, TAWIL R, TRISTANI-FIROUZI M, CANUN S, BENDAHHOUS S, TSUNODA A, DONALDSON MR, IANNACCONE ST, BRUNT E, BAROHN R, CLARK J, DEYMEER F, GEORGE AL JR, FISH FA, HAHN A, NITU A, OZDEMIR C, SERDAROGLU P, SUBRAMONY SH, WOLFE G, FU YH, PTACEK LJ. Mutations in Kir2.1 cause the QT developmental and episodic electrical phenotypes of Andersen's syndrome. *Cell* **105**: 511-519, 2001.
- POSTMA AV, BEZZINA CR, DE VRIES JF, WILDE AA, MOORMAN AF, MANNES MM: Genomic organisation and chromosomal localisation of two members of the KCND ion channel family, KCND2 and KCND3. *Hum Genet* **106**: 614-619, 2000.
- ROZEN S, SKALETSKY HJ: Primer3 on the WWW for general users and for biologist programmers. *Methods Mol Biol* **132**: 365-386, 2000.
- SCHWARTZ PJ, MOSS AJ, VINCENT GM, CRAMPTON RS: Diagnostic criteria for the long QT syndrome: an update (Review). *Circulation* **88**: 782-784, 1993.
- SPLAWSKI I, SHEN J, TIMOTHY K, LEHMANN MH, PRIORI SG, ROBINSON JL, MOSS AJ, SCHWARTZ PJ, TOWBIN JA, VINCENT GM, KEATING MT: Spectrum of mutations in long-QT syndrome genes KVLQT1, HERG, SCN5A, KCNE1, and KCNE2. *Circulation* **102**: 1178-1185, 2000.
- SPLAWSKI I, TIMOTHY KW, DECHER N, KUMAR P, SACHSE FB, BEGGS AH, SANGUINETTI MC, KEATING MT. Severe arrhythmia disorder caused by cardiac L-type calcium channel mutation. *Proc Natl Acad Sci USA* **102**: 8089-8096, 2005.
- STENSON PD, BALL EV, MORT M, PHILLIPS AD, SHIEL JA, THOMAS NS, ABEYSINGLE S, KRAWCZAK M, COOPER DN: Jun. Human Gene Mutation Database (HGMD): 2003 update. *Hum Mutat* **21**: 577-581, 2003.
- TAWIL R, PTACEK LJ, PAVLAKIS SG, DEVIVO DC, PENN AS, OZDEMIR C, GRIGGS RC. Andersen's syndrome: potassium-sensitive paralysis, ventricular ectopy and dysmorphic features. *Ann Neurol* **35**: 326-330, 1994.

-
- TESTER DJ, WILL ML, HAGLUND CM, ACKERMAN MJ: Effect of clinical phenotype on yield of long QT syndrome genetic testing. *Heart Rhythm* **2**: 507-517, 2005.
- TSENG GN: Molecular structure of cardiac I_{to} channels: Kv4.2, Kv4.3, and other possibilities? *Cardiovasc Res* **41**: 16-18, 1999.
- VATTA M, ACKERMAN MJ, YE B, MAKIELSKI JC, UGHANZE EE, TAYLOR EW, TESTER DJ, BALIJEPALLI RC, FOELL JD, LI Z, KAMP TJ, TOWBIN JA. Mutant caveolin-3 induces persistent late sodium current and is associated with long-QT syndrome. *Circulation* **114**: 2104-2112, 2006.
- WALLACE RH, SCHEFFER IE, PARASIVAM G, BARNETT S, WALLACE GB, SUTHERLAND GR, BERKOVIC SF, MULLEY JC: Generalized epilepsy with febrile seizures plus: mutation of the sodium channel subunit SCN1B. *Neurology* **58**: 1426-1429, 2002.
-