

# Regulation of GluR6-PSD95-MLK3 Signaling in KA-Induced Epilepsy

Chong Li and Guang-Yi Zhang  
Xuzhou Medical College  
P. R. China

## 1. Introduction

Glutamate receptors are classified into two groups: metabotropic glutamate receptors (mGluRs) and ionotropic glutamate receptors (iGluRs). The ionotropic glutamate receptors are superfamily of ligand-gated cation channels that encompass three receptor families identified by the agonists that selectively activate them: *N*-methyl-D-aspartate (NMDA),  $\alpha$ -amino-3-hydroxy-5-methyl-4-isoxazole propionate (AMPA), and kainic acid (KA) receptors (Dingledine *et al.* 1999, Mayer & Armstrong 2004, Kew & Kemp 2005). KA is a potent exogenous agonist of KA receptors and AMPA receptors, and systemic administration of KA produces epilepsy in rats and mice accompanied by neuronal damage mainly in limbic structures. In particular, hippocampal pyramidal neurons are highly vulnerable to the excitotoxicity of KA (Sperk *et al.* 1983). KA-induced seizures in rodents have been widely used as a model of human temporal lobe epilepsy on the basis of both behavioral and pathological similarities (Ben-Ari 1985).

KA receptors are comprised of five different subunits: KA1, KA2, GluR5, GluR6 and GluR7 (Lilliu *et al.* 2002, Porter *et al.* 1997). It is reported that GluR6 subunit-deficient and *Jnk3* gene knock-out mice resistance to KA-induced seizures and neuronal toxicity (Yang *et al.* 1997, Mulle *et al.* 1998). And the GluR6 mediated JNK3 (c-Jun N-terminal kinase 3) signaling pathway has been pay more attention in the study of neuron damage during epilepsia. C terminus of GluR6 can bind to the PDZ1 domain of the postsynaptic density protein PSD95/SAP90 through specific interaction (Garcia *et al.* 1998, Mehta *et al.* 2001). Previous studies have also shown that MLK3 (mixed lineage kinase-3), an upstream kinase of JNK (Tibbles *et al.* 1996), can interact with the SH3 (Src homology) domain of PSD95 (Savinainen *et al.* 2001). The triple complex GluR6-PSD95-MLK3 may exist and facilitate JNK activation.

In our previous studies on brain ischemia, it has demonstrated that KA enhanced the assembly of GluR6-PSD95-MLK3 module, increased the autophosphorylation of MLK3 and the phosphorylation of MKK7 (mitogen-activated protein kinase kinase 7), JNK3, c-Jun and Bcl-2 (B-cell lymphoma 2), raised the expression of Fas-Ligand (FasL) and caused the release of Bax (Bcl-2 associated x protein) from Bcl-2/Bax dimmers and the release of cytochrome c from mitochondria (Pei *et al.* 2006). Consequently, the activation of Caspase 3 led to delayed neuronal death in the hippocampal CA1/CA3 subfield (Tian *et al.* 2005, Pei *et al.* 2005, Pan *et al.* 2005). The activation of mitochondrion-linked apoptotic signaling pathways after seizures, including activation of caspase-9, -3, and -8, has also been reported (Henshall *et al.* 2000). And we further found that KA-induced neuronal death is mediated by the GluR6-

PSD95-MLK3 signaling module via FasL/Fas and cytochrome c pathways in KA-induced seizures and interference of the interaction between GluR6 and PSD95 with a peptide can protect neurons from KA-induced death (Liu *et al.* 2006).

Regulation of GluR6 mediated apoptotic pathway has emerged as a possible approach to protect neuron damage against seizure. One idea is down-regulating excitatory GluR6-containing KA receptors by activation of inhibitory GABA receptors. GABA plays a key role in modulating neuronal activity via distinct receptor systems, the ionotropic GABA<sub>A</sub> and metabotropic GABA<sub>B</sub> receptors. It has been proposed that coactivation of GABA<sub>A</sub> and GABA<sub>B</sub> receptors induced by muscimol and baclofen respectively can result in neuroprotection during *in vitro* ischemia (Costa *et al.* 2004), and coapplication of the two agonists is more effective than when solely used (Zhang *et al.* 2007). Data acquired from our lab demonstrated that coapplication of muscimol with baclofen has neuroprotective effects in rat hippocampal CA1 and CA3 regions and inhibits the assembly of the GluR6-PSD95-MLK3 signaling module and subsequently activates JNK downstream signaling pathways (Li *et al.*).

## **2. Neuroprotective effects of peptide Tat-GluR6-9c and GABA receptors activation against neuronal death induced by KA in rat hippocampus**

Based on our previous study, activation of GluR6-PSD95-MLK3 signaling is an important reason for neuron death in rat KA-induced epilepsy model. Interference of this signaling might have protective effects against neuron death, so we designed two different strategies to carry out the goal. First, we constructed a peptide comprising the conserved nine COOH-terminal residues of GluR6 (Arg-Leu-Pro-Gly-Lys-Glu-Thr-Met-Ala, named GluR6-9c), which was fused to Tat protein (cell-membrane transduction domain of the human immunodeficiency virus-type 1, Tyr-Gly-Arg-Lys-Lys-Arg-Arg-Gln-Arg-Arg-Arg). The Tat-GluR6-9c peptide can be delivered into hippocampal neurons and destroy the interaction between GluR6 and PSD95, and further suppress the GluR6-PSD95-MLK3 signaling. Second, elevating the inhibition of GABA receptors can significantly decrease KAR-mediated excitation in KA-induced epilepsy. The major finding is that Muscimol and/or Baclofen can suppress the assembly of the GluR6-PSD95-MLK3 signaling. One possible explanation is that the activation of GABA<sub>A</sub> receptor by muscimol can induce the hyperpolarization of postsynaptic neurons via activating ligand-gated Cl<sup>-</sup> channels, which decrease the depolarization of the neurons (Attwell *et al.* 1993), and activation of G protein-coupled GABA<sub>B</sub> receptor by baclofen can attenuate glutamate release from presynaptic neurons (Moldavan *et al.* 2006). The mechanism and roles of these two strategies are described below.

### **2.1 Assembly of the GluR6-PSD95-MLK3 signaling module during seizure induced by KA in hippocampal CA1 and CA3/DG regions**

Immunoprecipitation and immunoblotting were performed to examine the interactions of GluR6 and MLK3 with PSD95 at various times of KA injection. The interactions of GluR6 and MLK3 with PSD95 increased rapidly after KA injection, reached peak levels at 6 h, and then gradually decreased to control levels at 3 days in both CA1 and CA3/DG regions.

### **2.2 Tat-GluR6-9c peptide suppresses the increased assembly of the GluR6-PSD95-MLK3 signaling module induced by KA in hippocampal CA1 and CA3/DG regions**

Tat-GluR6-9c, a GluR6 C terminus-containing peptide conjugated to the cell membrane transduction sequence of the human immunodeficiency virus Tat protein, can be delivered

into hippocampal neurons *in vitro* and *in vivo*. Reciprocal immunoprecipitation experiments demonstrated that the peptide perturbed the GluR6-PSD95-MLK3 signaling module. Administration of Tat-GluR6-9c 40 min prior to KA injection diminished the increased interactions of GluR6 and MLK3 with PSD95 at 6 h after kainate treatment in CA1 and CA3/DG subregions, whereas the protein levels of GluR6, PSD95, and MLK3 were not altered.

### **2.3 Tat-GluR6-9c inhibits the activation of MLK3, MKK7, and JNK induced by KA in hippocampal CA1 and CA3/DG regions**

KA treatment resulted in a remarkable increase in the phosphorylation of MLK3 in CA1 and CA3/DG regions. Pretreatment with Tat-GluR6-9c significantly diminished the increase in the phosphorylation of MLK3. And, the activation of MKK7 and JNK at 6 h after KA injection was significantly suppressed by application of the Tat-GluR6-9c peptide in CA1 and CA3/DG regions.

### **2.4 Tat-GluR6-9c inhibits the phosphorylation of c-Jun and the expression of FasL induced by KA in hippocampal CA1 and CA3/DG regions**

The phosphorylation and expression of transcription factor c-Jun was significantly increased at 6 and 12 h in both CA1 and CA3/DG regions after KA injection. Prior administration of Tat-GluR6-9c significantly diminished the increase in phospho-c-Jun at 6 h after KA treatment. The protein levels of c-Jun were not affected. The increased phosphorylation of c-Jun leads to increased expression of FasL. The expression of FasL increased rapidly at 6 h and returned to the basal level at 3 days in CA1 and CA3/DG regions. Prior application of Tat-GluR6-9c diminished the increased expression of FasL.

### **2.5 Tat-GluR6-9c decreases Bax expression and increases Bcl-2 expression induced by KA in hippocampal CA1 and CA3/DG regions**

It is known that Bcl-2 is an anti-apoptotic protein, whereas Bax is a pro-apoptotic protein. The expression of Bax increased dramatically at 6 h after KA injection and lasted 3 days, whereas the level of Bcl-2 decreased sharply at 6 h after KA injection and reached the lowest at 3 days in the CA1 region. Prior application of Tat-GluR6-9c resulted in the decreased expression of Bax at 6 h after KA treatment in both CA1 and CA3/DG regions, whereas the level of Bcl-2 was obviously increased at 6 h after KA injection.

### **2.6 Tat-GluR6-9c attenuates Bax translocation and the release of cytochrome c induced by KA in Hippocampal CA1 and CA3/DG regions**

A previous study reported mitochondrial Bax accumulation after seizure (Henshall *et al.* 2002). Tat-GluR6-9c can inhibit Bax translocation in the mitochondrial fraction in both CA1 and CA3/DG regions. Moreover, Tat-GluR6-9c inhibited the release of cytochrome c from mitochondria to the cytosol in CA1 and CA3/DG fields.

### **2.7 Tat-GluR6-9c inhibits the activation of caspase-3 and neuronal apoptosis induced by KA in hippocampal CA1 and CA3/DG regions**

Tat-GluR6-9c pretreatment diminished the activation of caspase-3 at 6 h after KA injection. TUNEL (Terminal Transferase dUTP Nick End Labeling) staining was used to examine the apoptosis of CA1 and CA3 neuronal cells in the hippocampus. Administration of Tat-GluR6-

9c 40 min before KA injection significantly decreased TUNEL-positive cells. Tat-GluR6-9c significantly decreased neuronal degeneration (Fig. 1).

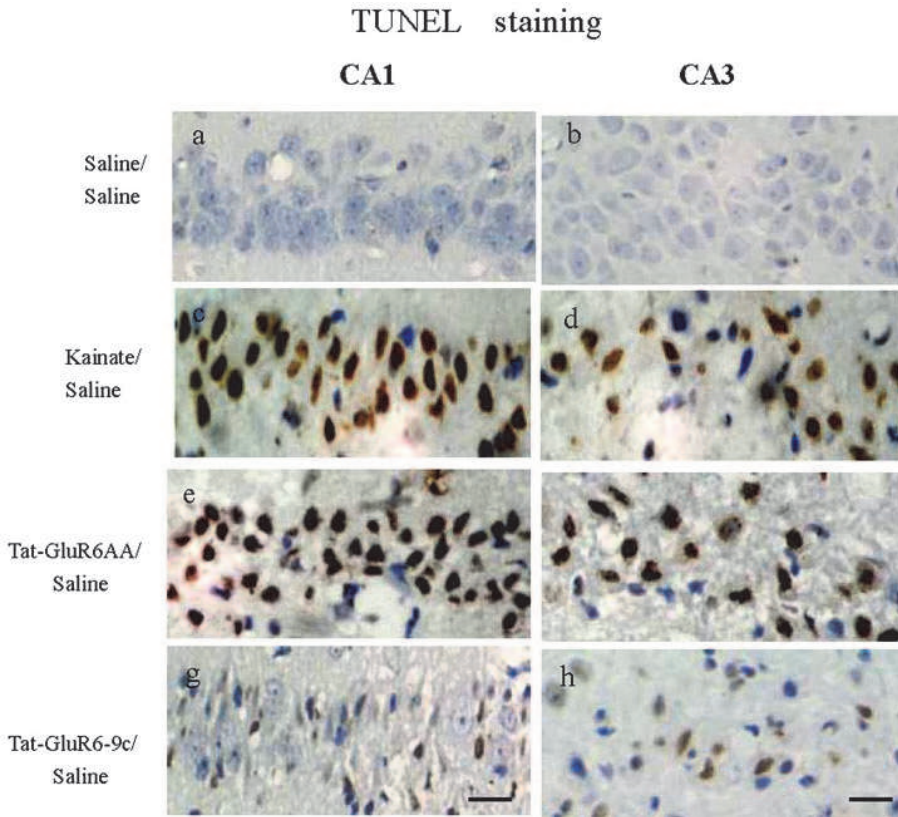


Fig. 1. Neuroprotection of peptide Tat-GluR6-9c in hippocampal CA1 and CA3 subfields.

### 2.8 Muscimol and baclofen suppress the increased assembly of the GluR6-PSD95-MLK3 signaling module induced by KA in hippocampal CA1 and CA3/DG regions

The GABA receptors can be activated by two GABA agonists: muscimol, a GABA<sub>A</sub> agonist, and baclofen, a GABA<sub>B</sub> agonist. Reciprocal immunoprecipitation experiments suggested that the administration of two agonists resulted in the disassembly of GluR6-PSD95-MLK3 signaling module. Co-administration of muscimol and baclofen 40 min prior to KA injection diminished the increased interactions of GluR6 and MLK3 with PSD95 at 6 h after KA treatment in CA1 and CA3/DG subregions, whereas the protein levels of GluR6, PSD95 and MLK3 were not altered.

### 2.9 Muscimol and baclofen inhibit the activation of MLK3, MKK7 and JNK3 induced by KA in hippocampal CA1 and CA3/DG regions

Pretreatment with muscimol and baclofen significantly diminished the increase of the MLK3 phosphorylation. Meanwhile, the activation of MKK7 at 6 h after KA injection was

significantly suppressed by co-application of muscimol and baclofen in CA1 and CA3/DG regions. Furthermore, similar results were obtained with JNK3.

### **2.10 Muscimol and baclofen inhibit the phosphorylation of c-Jun and the expression of FasL induced by KA in hippocampal CA1 and CA3/DG regions**

Prior administration of muscimol and baclofen significantly diminished the increase of phospho-c-Jun at 6 h after KA treatment. Prior application of muscimol and baclofen attenuated the increased expression of FasL at 6 h induced by KA in hippocampal CA1 and CA3/DG regions.

### **2.11 Muscimol and baclofen decrease Bax expression and increase Bcl-2 expression induced by KA in hippocampal CA1 and CA3/DG regions**

Prior application of muscimol and baclofen resulted in the decreased expression of Bax at 6 h after KA treatment in both CA1 and CA3/DG regions, whereas the level of Bcl-2 was obviously increased at 6 h after KA injection.

### **2.12 Muscimol and baclofen attenuate Bax translocation and the release of cytochrome c induced by KA in hippocampal CA1 and CA3/DG regions**

Muscimol and baclofen inhibited Bax translocation in the mitochondrial fraction at 6 h after KA administration compared with the saline control in both CA1 and CA3/DG regions. In the cytosolic fraction, cytochrome c immunoreactivity was evident as a single band at 6 h of KA injection. However, it was weakly detected in the saline group. A significant amount of mitochondrial cytochrome c was detected in the saline group, and it decreased at 6 h after KA injection corresponding to a marked increase in the cytosolic fraction. Moreover, muscimol and baclofen inhibited the release of cytochrome c from mitochondria to the cytosol in CA1 and CA3/DG fields.

### **2.13 Muscimol and baclofen inhibit the activation of caspase-3 and neuronal apoptosis induced by KA in hippocampal CA1 and CA3/DG regions**

Muscimol and baclofen pretreatment diminished the activation of caspase-3 at 6 h after KA injection. Furthermore, significant numbers of TUNEL-positive cells were observed in the KA-treated group after 7 days, but administration of muscimol and baclofen 40 min before KA injection significantly decreased TUNEL-positive cells.

## **3. Conclusion**

KA induced the assembly of the GluR6-PSD95-MLK3 signaling module and subsequently activated JNK downstream signaling pathways, ultimately resulting in neuronal cell death. Application of Tat-GluR6-9c, a GluR6 C terminus-containing peptide, suppressed the clustering of GluR6 in the postsynaptic regions by competitively binding to the PDZ1 domain of PSD95 and subsequently inhibited the assembly of the GluR6-PSD95-MLK3 signaling module. As a result, the peptide attenuated the activation of MLK3 and JNK. Furthermore, Tat-GluR6-9c inhibited the activation of the nuclear and non-nuclear pathways of JNK induced by KA. Notably, the peptide had neuroprotective effects against rat epileptic brain damage. In conclusion, the kainate receptor subunit GluR6 plays an important role in

brain damage induced by KA, and Tat-GluR6-9c provides a new approach for epileptic seizure therapy.

Co-application of muscimol (GABA<sub>A</sub> receptor agonist) and baclofen (GABA<sub>B</sub> receptor agonist) inhibited the assembly of the GluR6-PSD95-MLK3 signaling module. The two agonists attenuated the activation of MLK3 and JNK. Furthermore, muscimol and baclofen inhibited the activation of the nuclear and non-nuclear pathways of JNK induced by KA. Notably, the coapplication the two agonists had neuroprotective effects against rat epileptic brain damage. This highlighted that the balance between neuronal excitation and inhibition is critical for maintaining normal function.

#### 4. Acknowledgment

This work was supported by Grant from the Key Project of the National Natural Science Foundation of China (30330190), grants from the National Natural Science Foundation of China (No. 90608015; No. 30870543; No. 31000360), the Natural Science Funds of Jiangsu Province (No. BK2010176), the Education Departmental Nature Science Funds of Jiangsu Province (09KJB310015) and the Science and Technology Development Funds (XF10C077). Dr. Chong Li was supported by "Six Talent Peaks Program" of Jiangsu Province of China in 2009.

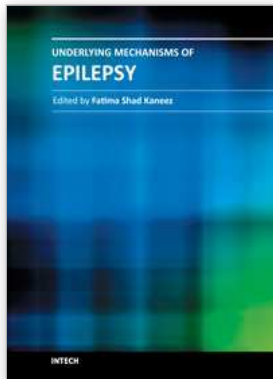
#### 5. References

- Attwell, D., Barbour, B. and Szatkowski, M. (1993) Nonvesicular release of neurotransmitter. *Neuron*, 11, 401-407.
- Ben-Ari, Y. (1985) Limbic seizure and brain damage produced by kainic acid: mechanisms and relevance to human temporal lobe epilepsy. *Neuroscience*, 14, 375-403.
- Costa, C., Leone, G., Saulle, E., Pisani, F., Bernardi, G. and Calabresi, P. (2004) Coactivation of GABA(A) and GABA(B) receptor results in neuroprotection during in vitro ischemia. *Stroke*, 35, 596-600.
- Dingledine, R., Borges, K., Bowie, D. and Traynelis, S. F. (1999) The glutamate receptor ion channels. *Pharmacological reviews*, 51, 7-61.
- Garcia, E. P., Mehta, S., Blair, L. A., Wells, D. G., Shang, J., Fukushima, T., Fallon, J. R., Garner, C. C. and Marshall, J. (1998) SAP90 binds and clusters kainate receptors causing incomplete desensitization. *Neuron*, 21, 727-739.
- Henshall, D. C., Araki, T., Schindler, C. K., Lan, J. Q., Tiekoter, K. L., Taki, W. and Simon, R. P. (2002) Activation of Bcl-2-associated death protein and counter-response of Akt within cell populations during seizure-induced neuronal death. *J Neurosci*, 22, 8458-8465.
- Henshall, D. C., Chen, J. and Simon, R. P. (2000) Involvement of caspase-3-like protease in the mechanism of cell death following focally evoked limbic seizures. *J Neurochem*, 74, 1215-1223.
- Kew, J. N. and Kemp, J. A. (2005) Ionotropic and metabotropic glutamate receptor structure and pharmacology. *Psychopharmacology*, 179, 4-29.
- Li, C., Xu, B., Wang, W. W., Yu, X. J., Zhu, J., Yu, H. M., Han, D., Pei, D. S. and Zhang, G. Y. (2010) Coactivation of GABA receptors inhibits the JNK3 apoptotic pathway via

- disassembly of GluR6-PSD-95-MLK3 signaling module in KA-induced seizure. *Epilepsia*, 51, 391-403.
- Lilliu, V., Perrone-Capano, C., Pernas-Alonso, R., Diaz Trelles, R., Luca Colucci d'Amato, G., Zuddas, A. and di Porzio, U. (2002) Ontogeny of kainate receptor gene expression in the developing rat midbrain and striatum. *Brain research*, 104, 1-10.
- Liu, X. M., Pei, D. S., Guan, Q. H., Sun, Y. F., Wang, X. T., Zhang, Q. X. and Zhang, G. Y. (2006) Neuroprotection of Tat-GluR6-9c against neuronal death induced by kainate in rat hippocampus via nuclear and non-nuclear pathways. *J Biol Chem*, 281, 17432-17445.
- Mayer, M. L. and Armstrong, N. (2004) Structure and function of glutamate receptor ion channels. *Annual review of physiology*, 66, 161-181.
- Mehta, S., Wu, H., Garner, C. C. and Marshall, J. (2001) Molecular mechanisms regulating the differential association of kainate receptor subunits with SAP90/PSD-95 and SAP97. *J Biol Chem*, 276, 16092-16099.
- Moldavan, M. G., Irwin, R. P. and Allen, C. N. (2006) Presynaptic GABA(B) receptors regulate retinohypothalamic tract synaptic transmission by inhibiting voltage-gated Ca<sup>2+</sup> channels. *Journal of neurophysiology*, 95, 3727-3741.
- Mulle, C., Sailer, A., Perez-Otano, I. et al. (1998) Altered synaptic physiology and reduced susceptibility to kainate-induced seizures in GluR6-deficient mice. *Nature*, 392, 601-605.
- Pan, J., Zhang, Q. G. and Zhang, G. Y. (2005) The neuroprotective effects of K252a through inhibiting MLK3/MKK7/JNK3 signaling pathway on ischemic brain injury in rat hippocampal CA1 region. *Neuroscience*, 131, 147-159.
- Pei, D. S., Guan, Q. H., Sun, Y. F., Zhang, Q. X., Xu, T. L. and Zhang, G. Y. (2005) Neuroprotective effects of GluR6 antisense oligodeoxynucleotides on transient brain ischemia/reperfusion-induced neuronal death in rat hippocampal CA1 region. *Journal of neuroscience research*, 82, 642-649.
- Pei, D. S., Wang, X. T., Liu, Y. et al. (2006) Neuroprotection against ischaemic brain injury by a GluR6-9c peptide containing the TAT protein transduction sequence. *Brain*, 129, 465-479.
- Porter, R. H., Eastwood, S. L. and Harrison, P. J. (1997) Distribution of kainate receptor subunit mRNAs in human hippocampus, neocortex and cerebellum, and bilateral reduction of hippocampal GluR6 and KA2 transcripts in schizophrenia. *Brain Res*, 751, 217-231.
- Savinainen, A., Garcia, E. P., Dorow, D., Marshall, J. and Liu, Y. F. (2001) Kainate receptor activation induces mixed lineage kinase-mediated cellular signaling cascades via post-synaptic density protein 95. *J Biol Chem*, 276, 11382-11386.
- Sperk, G., Lassmann, H., Baran, H., Kish, S. J., Seitelberger, F. and Hornykiewicz, O. (1983) Kainic acid induced seizures: neurochemical and histopathological changes. *Neuroscience*, 10, 1301-1315.
- Tian, H., Zhang, Q. G., Zhu, G. X., Pei, D. S., Guan, Q. H. and Zhang, G. Y. (2005) Activation of c-Jun NH2-terminal kinase 3 is mediated by the GluR6.PSD-95.MLK3 signaling module following cerebral ischemia in rat hippocampus. *Brain Res*, 1061, 57-66.

- Tibbles, L. A., Ing, Y. L., Kiefer, F., Chan, J., Iscove, N., Woodgett, J. R. and Lassam, N. J. (1996) MLK-3 activates the SAPK/JNK and p38/RK pathways via SEK1 and MKK3/6. *EMBO J*, 15, 7026-7035.
- Yang, D. D., Kuan, C. Y., Whitmarsh, A. J., Rincon, M., Zheng, T. S., Davis, R. J., Rakic, P. and Flavell, R. A. (1997) Absence of excitotoxicity-induced apoptosis in the hippocampus of mice lacking the Jnk3 gene. *Nature*, 389, 865-870.
- Zhang, F., Li, C., Wang, R., Han, D., Zhang, Q. G., Zhou, C., Yu, H. M. and Zhang, G. Y. (2007) Activation of GABA receptors attenuates neuronal apoptosis through inhibiting the tyrosine phosphorylation of NR2A by Src after cerebral ischemia and reperfusion. *Neuroscience*, 150, 938-949.





## **Underlying Mechanisms of Epilepsy**

Edited by Prof. Fatima Shad Kaneez

ISBN 978-953-307-765-9

Hard cover, 354 pages

**Publisher** InTech

**Published online** 26, September, 2011

**Published in print edition** September, 2011

This book is a very provocative and interesting addition to the literature on Epilepsy. It offers a lot of appealing and stimulating work to offer food of thought to the readers from different disciplines. Around 5% of the total world population have seizures but only 0.9% is diagnosed with epilepsy, so it is very important to understand the differences between seizures and epilepsy, and also to identify the factors responsible for its etiology so as to have more effective therapeutic regime. In this book we have twenty chapters ranging from causes and underlying mechanisms to the treatment and side effects of epilepsy. This book contains a variety of chapters which will stimulate the readers to think about the complex interplay of epigenetics and epilepsy.

### **How to reference**

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Chong Li and Guang-Yi Zhang (2011). Regulation of GluR6-PSD95-MLK3 Signaling in KA-Induced Epilepsy, Underlying Mechanisms of Epilepsy, Prof. Fatima Shad Kaneez (Ed.), ISBN: 978-953-307-765-9, InTech, Available from: <http://www.intechopen.com/books/underlying-mechanisms-of-epilepsy/regulation-of-gluR6-psd95-mlk3-signaling-in-ka-induced-epilepsy>

# **INTECH**

open science | open minds

### **InTech Europe**

University Campus STeP Ri  
Slavka Krautzeka 83/A  
51000 Rijeka, Croatia  
Phone: +385 (51) 770 447  
Fax: +385 (51) 686 166  
[www.intechopen.com](http://www.intechopen.com)

### **InTech China**

Unit 405, Office Block, Hotel Equatorial Shanghai  
No.65, Yan An Road (West), Shanghai, 200040, China  
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元  
Phone: +86-21-62489820  
Fax: +86-21-62489821

© 2011 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the [Creative Commons Attribution-NonCommercial-ShareAlike-3.0 License](#), which permits use, distribution and reproduction for non-commercial purposes, provided the original is properly cited and derivative works building on this content are distributed under the same license.