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Long distance effect on ligand-gated ion channels extracellular domain may affect interactions with the intracellular machinery

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Modulation of receptor trafficking is critical for controlling neurotransmission. A $\gamma 2(R43Q)$ point mutation on GABA_A receptor subunit is linked to epilepsy in human. We recently analyzed the effect of this amino-acid substitution on GABA_A receptor trafficking and showed that this mutation as well as agonist application, both affecting GABA_A receptor extracellular domain, have an effect on receptor endocytosis. By comparing homology models based on ligand gated ion channels in their active and resting states, we reveal that the $\gamma 2R43$ domain is located in a loop that is affected by motion resulting from receptor activation. Taken together, these results suggest that endocytosis of GABA_A receptors is linked to agonist induced conformational changes. We propose that ligand or modulator binding is followed by a whole chain of interconnections, including the intracellular domain, that may influence ligand-gated channel trafficking.

Fast neurotransmission relies greatly on ligand-gated ion channels (LGICs) that are involved in many physiological functions. Plasticity of neurotransmission in physiological and pathophysiological states depend on LGIC trafficking that is modulated by a number of different mechanisms including surface targeting, mobility, and endocytosis.¹⁻³ GABA_ARs involved in fast inhibitory neurotransmission are also regulated by the exchange between surface and intracellular compartments via a constitutive clathrin-mediated dynamin-dependent endocytosis

pathway.⁴ This constitutive internalization is modulated by intracellular mechanisms and is altered in pathological conditions.⁵⁻⁹ Other LGIC such as AMPA or P2X receptors are also constitutively internalized by a clathrin-dependent endocytosis. In contrast, NMDA receptors are stabilized via an interaction with PDZ domain proteins and are more stable at the postsynaptic membrane.¹⁰ Among P2X subtypes, P2X4-containing receptors are specifically and constitutively internalized.¹¹

Genetic evidence has revealed a direct link between epilepsy and GABA_ARs dysfunction, including trafficking alteration.¹²⁻¹⁴ These mutations also offer an opportunity to obtain new insights into GABA_AR structure and function.¹⁵ For example, an R43Q mutation located in the $\gamma 2$ -subunit N-terminal extracellular domain (Fig. 1A) is linked to childhood absence epilepsy and febrile seizure.^{13,14} We recently analyzed $\gamma 2(R43Q)$ trafficking and showed that the $\gamma 2$ subunit containing the R43Q mutation increased a clathrin- and dynamin-dependent endocytosis of GABA_ARs, hindering their detection on the cell surface.¹⁶ The $\gamma 2(R43Q)$ -dependent endocytosis was reduced by GABA_ARs antagonists gabazine and picrotoxin, acting at a different site suggesting an allosteric effect i.e., that $\gamma 2(R43Q)$ -containing GABA_ARs are in a conformational state that promotes internalization. Further experiments revealed that agonist exposure triggered an increase of wild-type GABA_AR endocytosis, both on native- and recombinant-GABA_ARs.¹⁶ Application of their respective agonists enhances also

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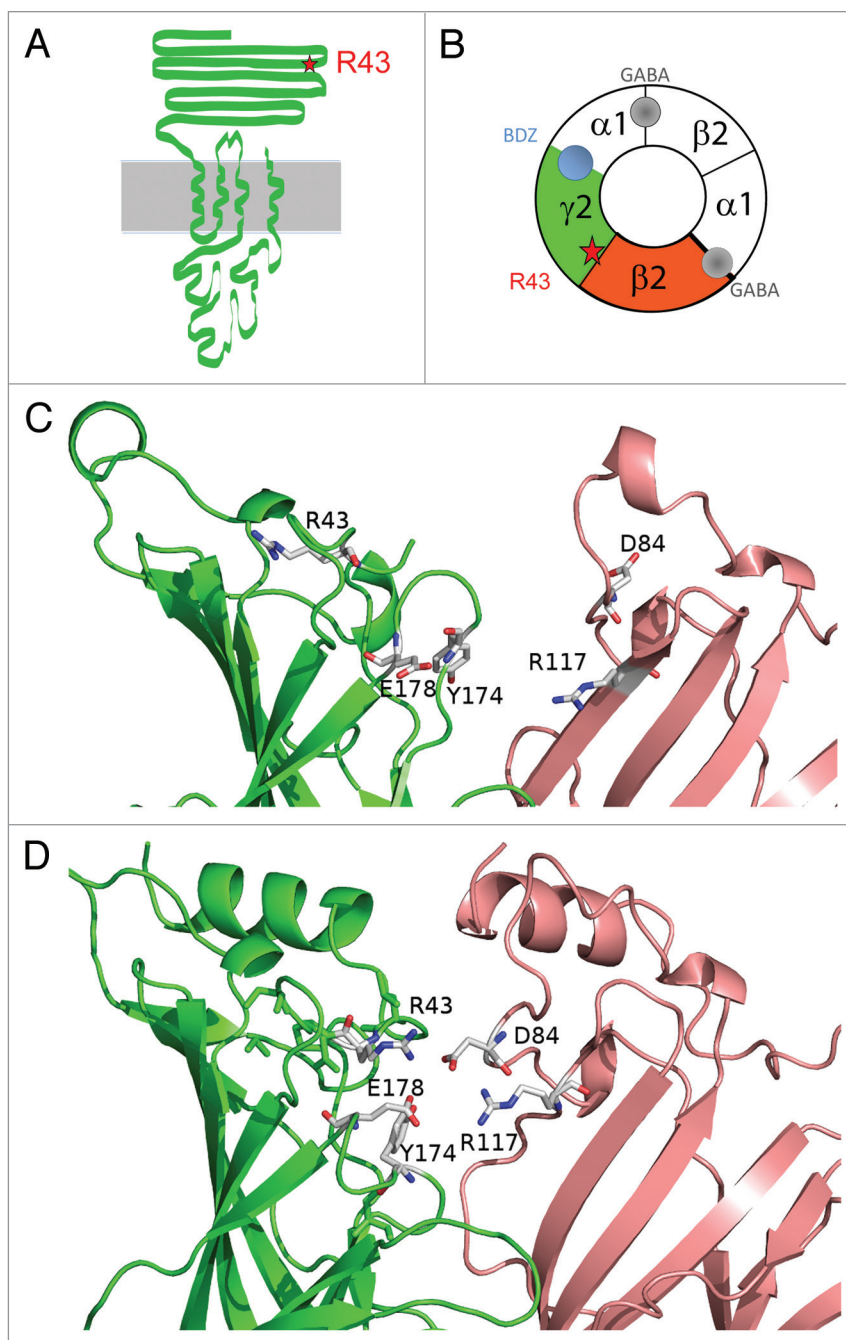


Figure 1. The $\gamma 2(R43Q)$ mutation destabilize the open-channel conformation. (A) Schematic representation of GABA_AR subunits showing a large N-terminal extracellular domain, 4 trans-membrane domains and a large cytoplasmic loop. The location of the $\gamma 2(R43Q)$ point mutation associated with childhood absence epilepsy and febrile seizure is indicated. (B) Schematic diagram of a $\alpha 1\beta 2\gamma 2$ GABA_AR which illustrates the 5 combined subunits that form the complex, the 2 GABA active binding sites at the $\beta 2$ and $\alpha 1$ interfaces (gray circles) and the benzodiazepine (BDZ, blue circle) allosteric binding site at the $\alpha 1$ and $\gamma 2$ interface. In current models, $\gamma 2R43$ (red star) is at the interface with $\beta 2$. (C,D) Model of a $\alpha 1\beta 2\gamma 2$ GABA_AR viewed from the outside. Here only the $\gamma 2$ and $\beta 2$ subunits are shown for clarity ($\gamma 2$ in green and $\beta 2$ in pink, see (B)). $\gamma 2$ (R43, Y174, E178) and $\beta 2$ (D84, R117) residues are represented by sticks. These residues are within loops identified as being involved in the channel-opening motion: (C) resting state model, (D) active state model.

the rate of AMPA- or P2X₄-receptor internalization suggesting that the increase might be caused by an agonist-induced

conformational change in the receptor promoting an interaction with components of the endocytotic machinery.¹¹

The GABA_AR extracellular domain contains binding sites for agonists and allosteric modulators (Fig. 1B), while the intracellular domain mediates interactions with trafficking factors.^{2,6,8,17} Consequently, our findings¹⁶ suggest that GABA_AR internalization is driven by a global conformational change. Molecular models show that the $\gamma 2R43$ residue is at the $\gamma 2/\beta 2$ interface in the extracellular domain, on a loop positioned above the pocket, which is homologous to the GABA binding sites. Interestingly, many mutations in nicotinic receptors linked to diseases are at the interface between receptor subunits;¹⁸ they alter the gating allosterically, i.e., from a distance.^{18,19} A model indicates that $\gamma 2R43$ and $\gamma 2E178$ are connected through a bifurcated salt bridge: this model has been used to study the $\gamma 2(R43Q)$ mutation.^{12,20,21} One of these studies has suggested that these positions have a long-range allosteric effect.²⁰ In our new GABA_AR model derived from the Glutamate-gated chloride channel in the active state recently published,²² the R43 residue of the $\gamma 2$ -subunit is connected to Y174 and E178 from the loop B and to $\beta 2$ subunit via polar interactions that should be sensitive to the R43Q substitution and positioned on a loop thought to be involved in the channel-pore opening motion²³ (Fig. 1D). Here we show that these interactions are not present in our novel model of the resting state (Fig. 1C) which was based on the structure of a prokaryotic homolog published very recently.²⁴ These new models (i.e., resting and activated states) point out that the $\gamma 2R43$ domain is affected by the motion resulting from GABA_AR activation. This observation is consistent with an allosteric effect of the mutation. Moreover, electrophysiological recordings and kinetic analyses have shown that the long-distance effects of $\gamma 2(R43Q)$ substitution extend as far as the transmembrane domains.²⁰ Then, the extracellular domain might have an influence on receptor endocytosis in line with the current views on pentameric ligand-gated ion channels, describing a link between extracellular-, transmembrane-, and intracellular-domains.²⁵⁻²⁷ This also suggests that allosteric drugs in wide clinical use may have an influence on receptor trafficking.

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Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

References

1. Choquet D, Triller A. The dynamic synapse. *Neuron* 2013; 80:691-703; PMID:24183020; <http://dx.doi.org/10.1016/j.neuron.2013.10.013>
2. Luscher B, Fuchs T, Kilpatrick CL. GABAA receptor trafficking-mediated plasticity of inhibitory synapses. *Neuron* 2011; 70:385-409; PMID:21555068; <http://dx.doi.org/10.1016/j.neuron.2011.03.024>
3. Smith KR, Kittler JT. The cell biology of synaptic inhibition in health and disease. *Curr Opin Neurobiol* 2010; 20:550-6; PMID:20650630; <http://dx.doi.org/10.1016/j.conb.2010.06.001>
4. Kittler JT, Delmas P, Jovanovic JN, Brown DA, Smart TG, Moss SJ. Constitutive endocytosis of GABAA receptors by an association with the adaptin AP2 complex modulates inhibitory synaptic currents in hippocampal neurons. *J Neurosci* 2000; 20:7972-7; PMID:11050117
5. Bannai H, Lévi S, Schweizer C, Inoue T, Launey T, Racine V, Sibarita JB, Mikoshiba K, Triller A. Activity-dependent tuning of inhibitory neurotransmission based on GABAAR diffusion dynamics. *Neuron* 2009; 62:670-82; PMID:19524526; <http://dx.doi.org/10.1016/j.neuron.2009.04.023>
6. Jacob TC, Moss SJ, Jurd R. GABA(A) receptor trafficking and its role in the dynamic modulation of neuronal inhibition. *Nat Rev Neurosci* 2008; 9:331-43; PMID:18382465; <http://dx.doi.org/10.1038/nrn2370>
7. Kittler JT, Thomas P, Tretter V, Bogdanov YD, Haucke V, Smart TG, Moss SJ. Huntingtin-associated protein 1 regulates inhibitory synaptic transmission by modulating gamma-aminobutyric acid type A receptor membrane trafficking. *Proc Natl Acad Sci U S A* 2004; 101:12736-41; PMID:15310851; <http://dx.doi.org/10.1073/pnas.0401860101>
8. Leidenheimer NJ. Regulation of excitation by GABA(A) receptor internalization. *Results Probl Cell Differ* 2008; 44:1-28; PMID:17549438; http://dx.doi.org/10.1007/400_2007_039
9. Smith KR, Muir J, Rao Y, Browarski M, Gruenig MC, Sheehan DF, Haucke V, Kittler JT. Stabilization of GABA(A) receptors at endocytic zones is mediated by an AP2 binding motif within the GABA(A) receptor $\beta 3$ subunit. *J Neurosci* 2012; 32:2485-98; PMID:22396422; <http://dx.doi.org/10.1523/JNEUROSCI.1622-11.2011>
10. Roche KW, Standley S, McCallum J, Dune Ly C, Ehlers MD, Wenthold RJ. Molecular determinants of NMDA receptor internalization. *Nat Neurosci* 2001; 4:794-802; PMID:11477425; <http://dx.doi.org/10.1038/90498>
11. Bobanovic LK, Royle SJ, Murrell-Lagnado RD. P2X receptor trafficking in neurons is subunit specific. *J Neurosci* 2002; 22:4814-24; PMID:12077178
12. Frugier G, Coussen F, Giraud MF, Odessa MF, Emerit MB, Boué-Grabot E, Garret M. A gamma 2(R43Q) mutation, linked to epilepsy in humans, alters GABAA receptor assembly and modifies subunit composition on the cell surface. *J Biol Chem* 2007; 282:3819-28; PMID:17148443; <http://dx.doi.org/10.1074/jbc.M608910200>
13. Tan HO, Reid CA, Single FN, Davies PJ, Chiu C, Murphy S, Clarke AL, Dibbens L, Krestel H, Mulley JC, et al. Reduced cortical inhibition in a mouse model of familial childhood absence epilepsy. *Proc Natl Acad Sci U S A* 2007; 104:17536-41; PMID:17947380; <http://dx.doi.org/10.1073/pnas.0708440104>
14. Wallace RH, Marini C, Petrou S, Harkin LA, Bowser DN, Panchal RG, Williams DA, Sutherland GR, Mulley JC, Scheffer IE, et al. Mutant GABA(A) receptor gamma2-subunit in childhood absence epilepsy and febrile seizures. *Nat Genet* 2001; 28:49-52; PMID:11326275; <http://dx.doi.org/10.1038/ng0501-49>
15. Noebels JL. The biology of epilepsy genes. *Annu Rev Neurosci* 2003; 26:599-625; PMID:14527270; <http://dx.doi.org/10.1146/annurev.neuro.26.010302.081210>
16. Chaumont S, André C, Perrais D, Boué-Grabot E, Taly A, Garret M. Agonist-dependent endocytosis of γ -aminobutyric acid type A (GABAA) receptors revealed by a $\gamma 2$ (R43Q) epilepsy mutation. *J Biol Chem* 2013; 288:28254-65; PMID:23935098; <http://dx.doi.org/10.1074/jbc.M113.470807>
17. Wang H, Bedford FK, Brandon NJ, Moss SJ, Olsen RW. GABA(A)-receptor-associated protein links GABA(A) receptors and the cytoskeleton. *Nature* 1999; 397:69-72; PMID:9892355; <http://dx.doi.org/10.1038/16264>
18. Changeux JP, Taly A. Nicotinic receptors, allosteric proteins and medicine. *Trends Mol Med* 2008; 14:93-102; PMID:18262468; <http://dx.doi.org/10.1016/j.molmed.2008.01.001>
19. Sine SM, Engel AG. Recent advances in Cys-loop receptor structure and function. *Nature* 2006; 440:448-55; PMID:16554804; <http://dx.doi.org/10.1038/nature04708>
20. Goldschen-Ohm MP, et al. An epilepsy-related region in the GABAA receptor mediates long-distance effects on GABA and benzodiazepine binding sites. *Mol Pharmacol* 2009; PMID:19846749
21. Sancar F, Czajkowski C. A GABAA receptor mutation linked to human epilepsy (gamma2R43Q) impairs cell surface expression of alphabeta gamma receptors. *J Biol Chem* 2004; 279:47034-9; PMID:15342642; <http://dx.doi.org/10.1074/jbc.M403388200>
22. Hibbs RE, Gouaux E. Principles of activation and permeation in an anion-selective Cys-loop receptor. *Nature* 2011; 474:54-60; PMID:21572436; <http://dx.doi.org/10.1038/nature10139>
23. Taly A, Corringer PJ, Grutter T, Prado de Carvalho L, Karplus M, Changeux JP. Implications of the quaternary twist allosteric model for the physiology and pathology of nicotinic acetylcholine receptors. *Proc Natl Acad Sci U S A* 2006; 103:16965-70; PMID:17077146; <http://dx.doi.org/10.1073/pnas.0607477103>
24. Sauguet L, et al. Crystal structures of a pentameric ligand-gated ion channel provide a mechanism for activation. *Proc Natl Acad Sci USA* 2013; PMID:24367074
25. Miller PS, Smart TG. Binding, activation and modulation of Cys-loop receptors. *Trends Pharmacol Sci* 2010; 31:161-74; PMID:20096941; <http://dx.doi.org/10.1016/j.tips.2009.12.005>
26. Peters JA, Cooper MA, Carland JE, Livesey MR, Hales TG, Lambert JJ. Novel structural determinants of single channel conductance and ion selectivity in 5-hydroxytryptamine type 3 and nicotinic acetylcholine receptors. *J Physiol* 2010; 588:587-96; PMID:19933751; <http://dx.doi.org/10.1113/jphysiol.2009.183137>
27. Tierney ML. Insights into the biophysical properties of GABA(A) ion channels: modulation of ion permeation by drugs and protein interactions. *Biochim Biophys Acta* 2011; 1808:667-73; PMID:21126507; <http://dx.doi.org/10.1016/j.bbame.2010.11.022>