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It is now well established that G protein-coupled receptors can exist not only as homodimers, but also as heterodimers or higher order oligomers. However, whether and how dimerization of the receptors is regulated is poorly understood. In this issue of The EMBO Journal, the team of Marc Landry provides evidence for an intriguing mechanism by which—under pathological conditions—GABAB receptor heterodimers at the cell surface are disrupted and thereby inactivated. An impressive set of experiments thus reveals a novel mechanism regulating the number of functional GABAB receptors in the plasma membrane and shows that the receptor heterodimer may not be as stable as we previously thought.

It is evident that dimerization and oligomerization at least of class A and C G protein-coupled receptors (GPCRs) play important roles in permitting or enhancing their cell surface trafficking (Milligan, 2010). The assembly process is thought to serve as a quality control mechanism to ensure that only fully mature and functional receptors reach the plasma membrane. The prototype of an obligatory heterodimer among GPCRs is the GABAB receptor, which controls excitability of neurons by mediating slow inhibitory neurotransmission (Gassmann and Bettler, 2012). Functional GABAB receptors are built from two related proteins termed as GABAB1 and GABAB2. Although both subunits display a similar structural organization—with a large extracellular domain containing a Venus fly-trap structure, seven transmembrane domains and a large intracellular C-terminal domain—they serve distinct, complementary functions. GABAB1 binds the orthosteric ligands whereas GABAB2 recruits the G protein and is required for cell surface trafficking of the receptor complex by masking an ER

**Figure 1** Novel mechanism regulating GABAB receptor signalling by disrupting the functional receptor heterodimer via interaction with 14-3-3ζ. Functional GABAB receptors are obligatory heterodimers built from GABAB1 and GABAB2 subunits. Under normal conditions, binding of GABA to the Venus fly-trap-like structure in the N-terminal domain of GABAB1 activates Gi/o proteins recruited by GABAB2 and thereby modulates distinct effector systems (adenylyl cyclases, potassium channels and voltage-gated Ca²⁺ channels). After induction of neuropathic pain by spinal nerve ligation, 14-3-3ζ is selectively upregulated in the spinal dorsal horn where painful sensory signals are processed and transmitted to the brain. 14-3-3ζ binds to the C-terminal domain of GABAB1 and disrupts by a yet-to-be identified mechanism the receptor dimer. This results in non-functional receptors and prevents GABAB receptor signalling.
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C-terminal domain of GABAB1 and has been shown that the ability of GABAB receptors at the cell surface is also determined by receptor trafficking, which includes endocytosis, recycling and degradation of the receptors (Benke, 2010). To maintain the required number of cell surface receptors for signalling under a given physiological status, all levels of receptor trafficking need to be precisely balanced. Changing the balance of the different trafficking mechanisms is one means to adjust receptor numbers to changing physiological conditions. An example of such regulation is the recently uncovered mechanism of the glutamate receptor-mediated downregulation of GABA receptors where the balance of recycling and degradation of the receptors is shifted towards degradation (Benke et al., 2012). Laffray et al. (2012) propose a novel and unexpected mechanism regulating the number of functional receptors at the cell surface. This mechanism is operative in vitro under pathological conditions and is based on the disruption of GABAB receptor heterodimers present in the plasma membrane by the GABAB1 interacting protein 14-3-3z.

Seven members of 14-3-3 proteins (14-3-3β, γ, ε, ζ, η, σ and τ) are ubiquitously expressed in mammals. 14-3-3 proteins bind predominantly to phosphoserine and phosphothreonine containing sequences and interact with hundreds of different partners to regulate a variety of cellular processes ranging from protein trafficking, apoptosis, cell cycle, signal transduction, cell adhesion and metabolism. It is therefore not surprising that alterations in the expression levels of 14-3-3 proteins and/or changes in the interaction status with target proteins are increasingly observed in diseases such as cancer, neurodegenerative diseases and epilepsy (Zhao et al., 2011).

Among 14-3-3 proteins, 14-3-3ζ interacts with the C-terminal domain of GABAB1 and has been shown in vitro to inhibit the heterodimerization of GABAB1 and GABAB2 C-terminal domains (Couve et al., 2001). However, the physiological and potential pathological function of this interaction was entirely unresolved. In a rat model of neuropathic pain (spinal nerve ligation), Laffray et al. (2012) observed a significant upregulation of 14-3-3ζ selectively in the ipsilateral dorsal horn of the lumbar spinal cord, the area where nociceptive signal processing in response to the injury takes place. Using several complementary methodologies including coimmunoprecipitation, colocalization immunofluorescence analysis, electron microscopy and two-photon fluorescence lifetime imaging, the authors demonstrated in vitro and in vivo that upregulation of 14-3-3ζ results in an increased interaction with GABAB1 in the plasma membrane and in a concomitant loss of GABAB1/GABAB2 association. This finding suggests that 14-3-3ζ disrupts existing heterodimers in the plasma membrane (Figure 1). As a consequence, the increased GABAB1/14-3-3ζ interaction rendered cell surface GABAB receptors non-functional and impaired GABAB receptor signalling.

The main unresolved and extremely interesting issue concerns the mechanism of heterodimer disruption by 14-3-3ζ. The interaction site of 14-3-3ζ partially overlaps with the coiled-coil domain in the C-terminal domain of GABAB1 (Couve et al., 2001). Coiled-coil domains are protein–protein interaction sites and are one of the domains thought to be involved in the heterodimerization of GABAB1 and GABAB2. The most obvious mechanism is a direct competition of 14-3-3ζ and GABAB2 for interaction with GABAB1. 14-3-3 proteins are inherently rigid proteins able to stabilize a given conformation after binding to its partner protein (Obsil and Obsilova, 2011). Thus, binding of 14-3-3ζ might arrest GABAB1 in a conformation that is non-permissive for GABAB2 heterodimerization. However, the apparent affinity of the interaction of 14-3-3ζ with GABAB1 is rather low and relatively high concentrations of 14-3-3ζ are required to prevent heterodimerization of GABAB1 and GABAB2 C-terminal domains in vitro (Couve et al., 2001). Given the relatively moderate increase of 14-3-3ζ in neuropathic spinal cord, a direct competition mechanism per se appears unlikely. On the other hand, 14-3-3 proteins predominantly bind to motifs containing phosphoserine and phosphothreonine. Therefore, phosphorylation of GABAB1 within the 14-3-3ζ binding site might thus foster the GABAB1/14-3-3ζ interaction. In this regard, it would be important to test whether serine or threonine residues within the 14-3-3ζ binding site are phosphorylated in chronic pain states and whether phosphorylation is required for 14-3-3ζ interaction.

An alternative mechanism may be based on the scaffolding properties of 14-3-3 proteins. 14-3-3 proteins act as dimers and thus harbour at least two protein interaction sites (Obsil and Obsilova, 2011). Therefore, 14-3-3ζ may target a second protein or a protein complex to GABAB receptors that forces the receptor complex to dissociate and prevent reassociation. Proteomic analyses of isolated GABAB1/14-3-3ζ complexes are needed to address this issue.

Another important aspect of the paper is that it sheds some light on the involvement of GABAB receptors in neuropathic pain. So far, there is no coherent picture on the contribution of GABAB receptors to chronic pain states. However, there is increasing evidence that diminished GABAB receptor activity due to downregulation of the receptors might play a role in at least some models of neuropathic pain (Zeilhofer et al., 2012). Although there might be distinct mechanisms downregulating functional GABAB receptors in chronic pain conditions, disruption of GABAB receptor heterodimers via upregulation of 14-3-3ζ appears to be a contributing factor. In their neuropathic pain model, Laffray et al. (2012) observed a diminished analgesic activity of the intrathecally injected GABAB receptor agonist baclofen. Preventing the binding of 14-3-3ζ to GABAB Receptors via knocking-down 14-3-3ζ with siRNA or by using a synthetic peptide disrupting the GABAB1/14-3-3ζ interaction restored expression of GABAB receptor heterodimers in the plasma membrane and consequently enhanced the analgesic effect of baclofen. Even more important, disruption of the 14-3-3ζ/GABAB1 interaction by injection of the interfering synthetic peptide alone in the absence of baclofen partially reversed pain in the neuropathic rats. This finding implies that diminished GABAB receptor signalling contributes to the expression of neuropathic pain. These results might be a starting point for a therapeutic strategy to reduce neuropathic pain based on reversing the GABAB1/14-3-3ζ interaction. There are already small molecule inhibitors of 14-3-3 protein–protein interactions under development (Zhao et al., 2011), which might be useful for testing the feasibility of such an approach.
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