The endocannabinoid system: an overview

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ENDOCANNABINOID SYSTEM: METABOLISM AND TARGETS OF ENDOCANNABINOIDs

Starting from 1992, when anandamide (AEA) was identified for the first time in the porcine brain (Devane et al., 1992), numerous studies contributed to the current state of knowledge regarding all elements that form the “endocannabinoid system (ECS)” (Maccarrone et al., 2010). Endocannabinoids (eCBs) are lipid mediators, isolated from brain and peripheral tissues that include amides, esters, and ethers of long chain polyunsaturated fatty acids; they mimic the action of Δ⁹-tetrahydrocannabinol (THC) in different biological processes. Until now, the most bioactive eCBs are anandamide (arachidonylethanolamide; AEA) and 2-arachidonoylglycerol (2-AG), yet the eCBs family includes also virodhamine, noladin ether, and 2-arachidonoylglycerol (2-AG), and we will discuss the therapeutic potential of new ECS-oriented drugs.

Upon the identification of anandamide (AEA) in the porcine brain, numerous studies contributed to the current state of knowledge regarding all elements that form the “endocannabinoid system (ECS).” How this complex system of receptors, ligands, and enzymes is integrated in helping to regulate fundamental processes at level of central nervous and peripheral systems and how its regulation and dysregulation might counteract disturbances of such functions, is nowadays still under investigation. However, the most recent advances on the physiological distribution and functional role of ECS allowed the progress of various research tools aimed at the therapeutic exploitation of endocannabinoid (eCB) signaling, as well as the development of novel drugs with pharmacological advantages. Here, we shall briefly overview the metabolic and signal transduction pathways of the main eCBs representatives, AEA, and 2-arachidonoylglycerol (2-AG), and we will discuss the therapeutic potential of new ECS-oriented drugs.

Keywords: anandamide, 2-arachidonoylglycerol, endocannabinoids, metabolic pathways, signal transduction
FIGURE 1 | Chemical structures of biologically active eCBs and of the eCB-like compounds.

FIGURE 2 | Schematic representation of the main elements that constitute the endocannabinoid system. The synthesis of N-arachidonoyl-ethanolamine (AEA) is due to the activity of a NAPE-specific phospholipase D (NAPE-PLD), whereas a fatty acid amide hydrolase (FAAH) is responsible for its intracellular degradation to ethanolamine (EtNH$_2$) and arachidonic acid (AA). 2-Arachidonoylglycerol (2-AG) is released from membrane lipids through the activity of diacylglycerol lipase (DAGL), and it is hydrolyzed by a cytosolic monoacylglycerol lipase (MAGL) that releases glycerol and AA. A purported endocannabinoid membrane transporter (EMT) clears AEA and 2-AG from the extracellular space, and takes them up into the cell. Both AEA and 2-AG trigger several signal transduction pathways by acting at their targets, CB1, CB2, GPR55, and nuclear PPARs. AEA, but not 2-AG, binds intracellularly also TRPV1, and thus it is also designated as a true endovanilloid.

revised by a number of studies documenting the presence of CB$_1$ in several non-neuronal cells and tissues (Gong et al., 2006), and of CB$_2$ in the brain stem (van Sickle et al., 2005) and in neuronal cells upon exogenous insults (Viscomi et al., 2009). In addition, the non-selective cationic channel type-1 vanilloid receptor (transient receptor potential vanilloid 1, TRPV1), usually activated by capsaicin and by noxious stimuli-like heat and protons (Di Marzo and De Petrocellis, 2010), is an alternative target for AEA, but not for 2-AG. More recently, also nuclear receptors like the peroxisome proliferator-activated receptors (PPARs) have been added to the list of eCBs targets, activated under physiological and pathological conditions (Pistis and Melis, 2010). A schematic representation of eCBs, their receptors, biosynthetic and catabolic enzymes, as well as putative transporter, is depicted in Figure 2.
eCBs AND THEIR SIGNAL TRANSDUCTION PATHWAYS

The signal transduction pathways coupled to CB, TRPV1, and PPAR receptors are summarized in Table 1. Among the effects elicited by eCBs by binding to CB receptors, we should recall Ca\(^{2+}\) channels inhibition (including N-, P/Q-, and L-type channels), inhibition of adenylyl cyclase and subsequent decrease of cAMP-dependent protein kinase, which leads to decreased phosphorylation of the K\(^+\) channels, regulation of ionic currents, activation of focal adhesion kinase, stimulation of mitogen-activated protein kinase (MAPK) cascades (Pertwee, 2006), and specifically ERK, p38 MAPK cascades (Derkinderen et al., 2001; Gertsch et al., 2004), and the stimulation of additional intracellular pathways including the phosphatidylinositol 3-kinase (PI3K)/Akt pathway through CB2 (Molina-Holgado et al., 2002).

Unlike CB2, CB1 receptors are associated to special membrane microdomains, called “lipid rafts” (LR) that modulate CB1-dependent signaling pathways. The functional relationship between CB1 and LR is affected by cholesterol content; in particular, membrane cholesterol enrichment in both primary and immortalized cell lines reduces the binding to CB1 and subsequent G-protein dependent signaling through adenylyl cyclase and MAPK (Bari et al., 2005). Moreover, the disruption of LRs by cholesterol depletion modifies AEA-induced endocytosis of CB1, which apparently loses the capacity to be directed toward the lysosomal compartment. Therefore, LRs, besides representing a favorable platform to regulate CB1 signaling, might also represent a cellular device for its intracellular trafficking (Sarnataro et al., 2005; Dainese et al., 2007). The general model to explain the neuromodulatory actions of AEA involves the release of eCBs from a postsynaptic neuron upon stimulation, then the back diffusion to presynaptic terminals, where AEA activates CB1 receptors, thus modulating neuronal membrane permeability to Ca\(^{2+}\) and K\(^{+}\) ions and the activity of adenylyl cyclase. The final outcome is a modified action of neurotransmitters (Di Marzo and De Petrocellis, 2010).

Table 1 | Signal transduction pathways triggered by eCBs at different target receptors.

<table>
<thead>
<tr>
<th>Receptor</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB1 and CB2</td>
<td>↓ Adenylyl cyclase</td>
</tr>
<tr>
<td></td>
<td>↑ Focal adhesion kinase (FAK) and mitogen-activated protein kinase (MAPK)</td>
</tr>
<tr>
<td></td>
<td>↑ ERK, p38 through CB1, and PI3K/Akt through CB2</td>
</tr>
<tr>
<td></td>
<td>↑ K(^{+}) channels</td>
</tr>
<tr>
<td></td>
<td>↓ Ca(^{2+}) channels</td>
</tr>
<tr>
<td>GPR55</td>
<td>↑ Intracellular [Ca(^{2+})]</td>
</tr>
<tr>
<td></td>
<td>↑ RhoA, Rac, and Cdc42</td>
</tr>
<tr>
<td></td>
<td>↑ ERK phosphorylation</td>
</tr>
<tr>
<td>TRPV1</td>
<td>↑ Intracellular [Ca(^{2+})]</td>
</tr>
<tr>
<td></td>
<td>↑ Caspasas</td>
</tr>
<tr>
<td></td>
<td>↑ Cytochrome c release</td>
</tr>
<tr>
<td></td>
<td>↑ Mitochondrial uncoupling</td>
</tr>
<tr>
<td></td>
<td>↑ Pro-apoptotic kinases</td>
</tr>
<tr>
<td>PPARs</td>
<td>↑ ROS</td>
</tr>
<tr>
<td></td>
<td>↑ Tyrosine kinases</td>
</tr>
<tr>
<td></td>
<td>↑ Adiponectin and lipoprotein lipase</td>
</tr>
</tbody>
</table>

The activation of GPR55, the purported “CB3” cannabinoid receptor, has been linked to (1) intracellular Ca\(^{2+}\) increase (Lauckner et al., 2008); (2) activation of the small GTPase proteins RhoA, Rac, and Cdc42 (Ryberg et al., 2007; Henstridge et al., 2009), and (3) ERK phosphorylation (Oka et al., 2007, 2009). Additionally, by triggering PPARs, eCBs exert a variety of long-term effects via genomic mechanisms and rapid non-genomic actions, which are opposite to those evoked by activation of “classical” surface cannabinoid receptors (Pistis and Melis, 2010). As a consequence, PPARs activation affects several physiological and pathological processes, such as lipid metabolism, energy balance, and feeding behavior, neuroprotection, epilepsy, circadian rhythms, inflammation, addiction, and cognitive functions (Pistis and Melis, 2010). However, AEA can also act as a modulator of other signaling pathways and, in fact, it has been observed that muscarinic and glutamate receptors have allosteric sites for AEA binding (Lanzafame et al., 2004). In this context, it should be underlined that there are several findings showing that eCBs modulate the signaling of several neuropeptides and hormones (Manzanares et al., 1999; Beinfeld and Connolly, 2001; Ghosal et al., 2002). This highly complex network of interactions is reflected in the multifaceted modulatory effects of eCBs on the regulation of brain and behavioral functions (López-Moreno et al., 2008).

PHYSIOLOGICAL ACTIONS OF ECS AND THERAPEUTIC PERSPECTIVES

The presence of ECS in vertebrates, mammals, and humans implies a role in several physiological processes, including appetite, cancer, cardiovascular diseases, fertility, immune functions, memory, neuroprotection, and pain modulation (Ligresti et al., 2009; Maccarrone et al., 2010) (Figure 3).

In the last 10 years, it has become clear that a dysregulation of ECS is connected to pathological conditions, and thus its modulation through inhibition of metabolic pathways and/or agonism or antagonism of its receptors has an enormous potential for research and intervention in multiple areas of human health.
Therefore, based on the therapeutic potential of THC, known since centuries as medicine for its palliative effects in several pathologies, plant-derived cannabinoids, synthetic cannabinoids, and eCBs have been tested as novel therapeutics in a wide range of clinical trials.

The neuroprotective effect of eCBs might be mediated by either CB1- or CB2-dependent mechanisms. Research studies using cb1−/− knock-out mice showed an increased mortality rate and an increased infarct area in cerebral ischemia models (Parmentier-Batteur et al., 2002). It has been reported that the administration of the CB1 synthetic agonist WIN 55.212–2 attenuated the neurological damage and reduced infarct size in artery occlusion induced in rats (Nagayama et al., 1999), and additionally it reduced the glial damage after hypoxic-ischemic brain injury in preterm lambs (Alonso-Alconada et al., 2010). The presence of CB2-positive cells in the brain during injury and in inflammatory neurodegenerative disorders might provide a novel strategy for cannabinoid-mediated intervention against stroke-induced neurodegeneration, without the unwanted psychoactive effects of CB1 receptor stimulation (Cunha et al., 2011). O-3853 and O-1966, two selective CB2 agonists, administrated 1 h before transient middle cerebral artery occlusion, significantly decreased the mobilization of white blood cells and their adherence to vascular endothelial cells, reduced the infarct size, and improved motor function after transient focal ischemia (Zhang et al., 2007, 2009).

According to these observations, pain management is preferably handled using CB2 agonists, such as HU-308 and AM-1241, which display significant relief in inflammatory and neuropathic pain models, without exhibiting central nervous system side effects (Hanus et al., 1999; Yao et al., 2006). In this context, new selective CB2 receptor modulators, designed by Glaxo Smith Kline as derivatives of pyrimidinecarboxamide, have been tested as good clinical candidates to treat inflammatory, acute, and chronic pain (Giblin et al., 2007, 2009).

In the past, several reports documented that the selective pharmacologic antagonism of the CB1 receptor improves lipid abnormalities associated with obesity, as well as neurodegenerative diseases and nicotine or alcohol dependence (Centonze et al., 2007; Di Marzo, 2008). Following the good outcome obtained in

Table 2 | Chemical structures and therapeutic potential of some ECS-targeted molecules.

<table>
<thead>
<tr>
<th>Chemical structure</th>
<th>Compound</th>
<th>ECS target</th>
<th>Diseases</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Chemical structure" /></td>
<td>PF-04457845</td>
<td>FAAH</td>
<td>Pain, Osteoarthritis</td>
<td>Ahn et al., 2011</td>
</tr>
<tr>
<td><img src="image" alt="Chemical structure" /></td>
<td>URB 597</td>
<td></td>
<td>Anxiety, Cannabis dependence, Hyperalgesia</td>
<td>Bortolato et al., 2007</td>
</tr>
<tr>
<td><img src="image" alt="Chemical structure" /></td>
<td>SR141716A</td>
<td>CB1</td>
<td>Eating disorder</td>
<td>Christopoulou and Kiortsis, 2011</td>
</tr>
<tr>
<td><img src="image" alt="Chemical structure" /></td>
<td>WIN 55.212–2</td>
<td></td>
<td>Ischemic stroke, Brain injury</td>
<td>Nagayama et al., 1999; Alonso-Alconada et al., 2010</td>
</tr>
<tr>
<td><img src="image" alt="Chemical structure" /></td>
<td>HU-308</td>
<td>CB2</td>
<td>Neuropathic pain</td>
<td>Hanus et al., 1999</td>
</tr>
<tr>
<td><img src="image" alt="Chemical structure" /></td>
<td>GSK554418A</td>
<td></td>
<td>Acute/chronic pain</td>
<td>Giblin et al., 2009</td>
</tr>
<tr>
<td><img src="image" alt="Chemical structure" /></td>
<td>GW842166X</td>
<td></td>
<td>Inflammatory pain</td>
<td>Giblin et al., 2007</td>
</tr>
</tbody>
</table>
various clinical trials, the best known CB1 blocker SR141617A, also called rimonabant (and commercially known as Acomplia®) was released on the worldwide market as anti-obesity drug, but only few months later it was withdrawn because of increased rates of depression, anxiety, and suicide among patients who received it (Christopoulos and Kiortsis, 2011). In addition, further concerns were raised considering the possible side effects of this weight loss pill on the reproductive functions and human infertility (Bari et al., 2011).

Alternative strategies to treat pain syndromes, such as neuropathic pain, fibromyalgia, but also spontaneous abortion, headache, psychiatric disorders, and neurodegenerative diseases, are based on the enhancement of the eCB tone, through the inhibition of eCBs-hydrolyzing enzymes (Lichtman and Chapman, 2001). The most promising FAAH inhibitor seems to be URB597 (also named KDS-4103), which has biochemical and behavioral effects during both sub-acute and chronic treatments. In rodents, once-daily dosing of URB597 for five weeks elicits antidepressant effects in chronically stressed animals, without altering CB1 receptor mRNA levels (Bortolato et al., 2007). Pfizer and Vernalis pharmaceutical companies focused on FAAH as main target to design and develop new molecules (PF-04457845 and V158866, respectively), that are being tested in clinical studies as potential therapies for a range of pain disorders, including osteoarthritis (Ahn et al., 2011). It is noteworthy that FAAH inhibitors, because of their own pharmacological properties, are attractive remedial also for cannabis dependence; in fact, they do not appear to evoke tolerance following long-term administration, and they do not display significant abuse liability (Clapper et al., 2009).

Table 2 reports some agonists, antagonists, and/or inhibitors of ECS designed for the treatment of several pathological conditions.

CONCLUSION

Almost 20 years after the identification of AEA, all members of ECS are nowadays considered intriguing targets for the development of selective and specific compounds able to modulate human pathophysiology. A deeper and more detailed understanding of proteins involved in eCBs metabolism and signal-transduction pathways could help to design compounds that might prolong the activity of eCBs in a time- and site-dependent way, excluding undesired psychotropic effects, and to develop transgenic mice, where different ECS elements can be knocked down or knocked in, allowing innovative therapeutic strategies in a vast panorama of pathologies.

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of 1-[(3-chlorophenylamo)lo]-1-methyl-1H-pyrole [3,2-c]-pyridin-7-yl]-1-morpholin-4-ylmethane (GS535441A), a brain penetrant 5-arachidonoyl CB2 agonist for the treatment of chronic pain. J. Med. Chem. 52, 5785–5788.


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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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