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PUFA-derived endocannabinoids: an overview

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Following on from the discovery of cannabinoid receptors, of their endogenous agonists (endocannabinoids) and of the biosynthetic and metabolic enzymes of the endocannabinoids, significant progress has been made towards the understanding of the role of the endocannabinoid system in both physiological and pathological conditions. Endocannabinoids are mainly n-6 long-chain PUFA (LCPUFA) derivatives that are synthesised by neuronal cells and inactivated via a two-step process that begins with their transport from the extracellular to the intracellular space and culminates in their intracellular degradation by hydrolysis or oxidation. Although the enzymes responsible for the biosynthesis and metabolism of endocannabinoids have been well characterised, the processes involved in their cellular uptake are still a subject of debate. Moreover, little is yet known about the roles of endocannabinoids derived from n-3 LCPUFA such as EPA and DHA. Here, I provide an overview of what is currently known about the mechanisms for the biosynthesis and inactivation of endocannabinoids, together with a brief analysis of the involvement of the endocannabinoids in both food intake and obesity. Owing to limited space, recent reviews will be often cited instead of original papers.

Anandamide: 2-arachidonoyl-glycerol: Cannabinoid receptors: Food intake: Obesity

By definition, endocannabinoids are derivatives (amides, esters and ethers) of a long-chain PUFA, specifically arachidonic acid, capable of binding and functionally activating the cannabinoid receptors(1). It was 1992 when the first endocannabinoid was isolated from brain and named anandamide (from Sanskrit word ananda ‘supreme joy’)(2,3). This is the ethanolamide of arachidonic acid, and is thought to be a partial CB1 and CB2 receptor agonist as well as a transient receptor potential vanilloid (TRPV)1 receptor agonist(2,4–6). The other widely investigated endocannabinoid, 2-arachidonoylglycerol (2-AG), is the arachidonate ester of glycerol that was isolated from peripheral tissues. This molecule is able to activate CB1 and CB2 receptors with similar potency and efficacy(7,8), and to interact with γ-aminobutyric acid receptors(9). Other endocannabinoids might be represented by both 2-AG ether (noladin ether), that binds to CB1 receptors with relatively more affinity that to CB2(10), and virodhamine, that is a CB2 receptor agonist and CB1 receptor partial agonist/antagonist(11). Other compounds that are thought to be endocannabinoids include N-arachidonoyl dopamine, that like anandamide behaves as an agonist at both CB1 and TRPV1 receptors(12) and antagonises the melastatin type 8 (TRPM-8) cation channels(13), N-dihomo-γ-linolenoyl ethanolamine and N-oleoyl dopamine(14). Besides the n-6 long-chain PUFA, our group recently reported evidence that also the ethanolamides of n-3 fatty acids, docosahexaenoyl-ethanolamide (DHEA) and eicosapentaenoyl-ethanolamide, derived mainly from fish oils in the human diet (DHA and EPA) can be classified as endocannabinoids(15). Indeed, we found that they both are able to bind to CB1 and CB2 receptors with reasonable potency and they functionally activate both receptors, although with low efficacy(15). DHEA was first discovered in brain tissue and retina(16,17).

Abbreviations: ABHD, α/β-hydrolase domain; 2-AG, 2-arachidonoyl-glycerol; COX, cyclooxygenase-2; DAGL, diacylglycerol lipase; DHEA, docosahexaenoyl-ethanolamide; FAAH, fatty acid amide hydrolase; NAPE, N-acyl-phosphatidyl-ethanolamine; TRPV, transient receptor potential vanilloid.

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In 2001, Berger et al., demonstrated that brain levels of the ethanolamines of DHA and EPA, DHEA and eicosapentaenoyl-ethanolamide (EPEA), in piglets were modulated by the amount of n-3 long-chain PUFA in the feed(18). Other studies have shown an increased formation of DHEA and EPEA in various tissues, including prostate and breast cancer cells, after administering fish oil or individual n-3 long-chain PUFA(19,20). Interestingly, we have also reported evidence that both DHEA and EPEA show greater anti-proliferative effects than their parent compounds, DHA and EPA, in two prostate cancer cell lines, LNCaP and PC3 cells(15). However, the mechanisms underlying these effects are not clearly understood yet. Furthermore, when released, endocannabinoids are accompanied by cannabinoid receptor-inactive, saturated and mono- or di-unsaturated congeners, which can influence their metabolism and function. They include palmitoylethanolamide, steaeroylethanolamide, oleoylethanolamide, oleamide, 2-linoeoyl-glycerol and 2-palmitoyl-glycerol. These compounds appear to have cannabinimetic activity but do not bind to the classical cannabinoid receptors. It might be possible that these molecules exert their cannabinimetic effects by acting as ‘entourage molecules’ that prevent anandamide or other true cannabinoids being degraded by specific metabolic enzymes(21). This hypothesis is supported by the following observations: (a) oleamide greatly increases the efficiency of anandamide binding to cannabinoid receptors(22); (b) both 2-palmitoyl- and 2-linoeoyl-glycerol have a similar facilitatory effect on 2-AG binding to both cannabinoid receptors as well as on the 2-AG inhibitory effect on forskolin-activated adenylate cyclase(22,23); (c) these ‘entourage’ effects were less pronounced in the presence of phenylmethylsulphonyl-fluoride, which inhibits the main metabolic enzyme of anandamide and 2-AG, thus suggesting that these effects were due, at least in part, to inhibition of endocannabinoid hydrolysis by the ‘entourage’ compounds(22). Other mechanisms potentially involved in the ‘entourage’ effects warrant further investigation.

Cannabinoid receptors

Cannabinoid CB1(24,25) and CB2(26) receptors belong to the G-protein-coupled receptor superfamily. Their activation inhibits adenylate cyclase and Ca2+ (N-and P/Q-type) channels, activates K+ channels and mitogen-activated protein kinase cascades(27), specifically extracellular signal-regulated kinases and p38 mitogen-activated protein kinase cascades(28,29). Cannabinoid CB1 receptors are mainly expressed in the central nervous system where they mediate inhibition of ongoing release of various neurotransmitters (acetylcholine, noradrenaline, dopamine, 5-hydroxytryptamine, γ-aminobutyric acid, glutamate, d-aspartate and cholecystokinin)(30,31), and at lower levels in tests, heart, vascular tissue and in immune cells. Within the central nervous system, CB1 receptors are highly expressed in the cerebral cortex, hippocampus, lateral caudate-putamen, substantia nigra pars reticulate, globus pallidus, entopeduncular nucleus and cerebellum as well as in the pain pathways in brain and spinal cord. In these areas endocannabinoids control processes such as cognition, memory, motor function and analgesia(32). Unlike CB2, CB1 receptors are associated with special membrane microdomains, named ‘lipid rafts’(33). This association is greatly affected by cholesterol content; indeed, membrane cholesterol enrichment in both primary and immortalised cell lines reduces the binding to CB1; instead cholesterol depletion modifies anandamide-induced endocytosis of CB1, which apparently loses the ability to be directed towards the lysosomal compartment(33). Importantly, the existence on the CB1 cannabinoid receptors of an allosteric binding site that can be recognised by synthetic small molecules was reported for the first time by our group(34). Whether the CB2 receptor, such as CB1, possesses an allosteric binding site, warrants further investigation. Cannabinoid CB2 receptors are mainly expressed in immune cells, and recently they have also been detected in microglia, astrocytes and in central neurons(35,36). Finally, the existence of a third type of cannabinoid receptor, GPR55, is still a subject of debate(37).

Endocannabinoids biosynthesis and uptake

Although the biosynthetic and metabolic pathways have been largely studied for the n-6 endocannabinoids, it is probably that similar routes can occur for the n-3 endocannabinoids. Endocannabinoids are not stored in cells such as classical neurotransmitters waiting to be released after cell stimulation, but instead they are rapidly formed from membrane phospholipids ‘on demand’, where and when needed, and immediately released to target cannabinoid receptors mainly locally. Although anandamide and 2-AG are similar in structure, these endocannabinoids exhibit some differences in terms of biochemical and metabolic pathways. Both endocannabinoids are produced at post-synaptic neurons. For anandamide, the main biosynthetic pathway consists of a two-step process: (1) formation of N-acyl-phosphatidyl-ethanolamine (NAPE) from phosphatidyl-ethanolamine by a calcium-dependent N-acyltransferase, and (2) hydrolysis of NAPE to form N-acyl ethanolamines in a process that is catalysed by NAPE-hydrolysing phospholipase D(38-40) (Fig. 1). Since cells lacking NAPE-phospholipase D are also able to synthesise anandamide, alternative pathways have been proposed(41-43) and they are summarised in Fig. 1. The main biosynthetic pathway for 2-AG consists of hydrolysis by phospholipase C of inositol phospholipids containing arachidonic acid at the sn-2 position and further hydrolysis by diacylglycerol lipase (DAGL) of the arachidonic acid-containing DAG to 2-AG(48) (Fig. 2). In 2003, human DAGL was cloned and further characterised(49). It exists as two closely related genes designated α and β(49). Pharmacological studies have revealed that during neural development, localisation of DAGLα and DAGLβ changes from pre- to post-synaptic elements, i.e. from axonal tracts in the embryo to dendritic fields in the
adult, suggesting a different need for 2-AG synthesis from pre- to the post-synaptic compartment during brain development. Furthermore, several studies suggest that DAGLα plays an essential role in the regulation of retrograde synaptic plasticity and neurogenesis. In support of this hypothesis, two recent studies suggest that: (1) DAGLα-knockout mice show marked (up to 80%) reductions in 2-AG levels in brain and spinal cord with concomitant decrease in arachidonic acid levels, whereas DAGLβ-knockout animals exhibited either no or up to 50% reduction in brain 2-AG levels; (2) several forms of retrograde endocannabinoid-mediated synaptic suppression, such as depolarisation-induced suppression of excitation and depolarisation-induced suppression of inhibition, were absent in hippocampus, cerebellum and striatum in DAGLα-knockout, but not in DAGLβ-knockout mice. Like anandamide, also 2-AG can be synthesised by alternative pathways. However, the physiological meaning of these proposed pathways is not yet clear. Endocannabinoids function as retrograde messengers. Indeed, after their biosynthesis, they are released from post-synaptic neurons upon postsynaptic depolarisation and/or receptor activation and act on presynaptic CB1 receptors to induce transient suppression of transmitter release. Two forms of short-term synaptic plasticity have been identified so far, named depolarisation-induced suppression of inhibition, which involves GABAergic transmission, and depolarisation-induced suppression of excitation, which involves glutameric transmission. These processes were found mainly in the hippocampus and cerebellum, where they seem to play an important role in physiological processes such as memory and motor coordination. Additional forms of synaptic transmission involve the induction of long-term synaptic plasticity, named long-term potentiation and long-term depression. After targeting their receptors, the endocannabinoids are inactivated by a two-step process. The first process is the endocannabinoid transport from the extracellular to the intracellular space, followed by their metabolism. Whether this cellular uptake depends on the presence of an ‘endocannabinoid membrane transporter’ is currently a subject for debate as no such transporter has yet been cloned. Recently, Fowler has elegantly reviewed the current state of the art of endocannabinoid uptake.

Endocannabinoid metabolism

Whatever is the mechanism by which endocannabinoids are taken up by cells, after the uptake, they are metabolised by hydrolysis or oxidation (Fig. 2).

Hydrolysis

Fatty acid amide hydrolase (FAAH) is the main enzyme involved in anandamide hydrolysis, and it is able to recognise as substrates also other N-acyl-ethanolamines.

Fig. 1. Schematic representation of anandamide and 2-arachidonoyl-glycerol biosynthesis routes. AEA, anandamide; NAPE, N-acylphosphatidyl-ethanolamine; NArPE, N-arachidonoylphosphatidylethanolamine; PLC, phospholipase C; PTPN22, protein tyrosine phosphatase; PLA2, phospholipase A2; PE, phosphatidyl-ethanolamine; PLD, phospholipase D; Abhd4, α/β-hydrolase 4; DAG, diacylglycerol.
such as oleamide, and N-acetyltaurines. FAAH is a membrane-associated serine hydrolase belonging to the amidase signature family. The catalytic triad is composed of Lys142, Ser217 and Ser241. This enzyme is widely distributed in various tissues of rat, mouse and human subjects, and its optimal pH lies within the range 8.5–10. Other enzymes involved in anandamide hydrolysis are N-acylethanolamine acid amidase and FAAH-2, this latter being an isozyme of FAAH-1 with about 20% sequence identity at the amino acid level, mainly expressed in human subjects and not in rodents. N-acylethanolamine acid amidase is an N-glycosylated protein, localised in the lysosomes or the Golgi apparatus with an optimal pH of 4.5–5. FAAH-2 is more effective at metabolizing oleamide than anandamide or other N-acyl-ethanolamines. FAAH-1 and FAAH-2 are located in the cytosolic and luminal sides of intracellular membranes, respectively. FAAH is also able to metabolise, although to a lesser extent, 2-AG. Recently, three ‘guardians’ of 2-AG signalling have been reported: monoacylglycerol lipase, α/β-hydrolase domain (ABHD)-6 and ABHD-12. As recently reviewed, MAG lipase is a serine hydrolase belonging to the α/β-hydrolase superfamily, whose catalytic triad is composed of Ser122, Asp239 and His269. It was originally purified, and subsequently cloned from adipose tissue, and it is detected in both cytosol and membrane preparation. This enzyme accounts for about 80–85% of 2-AG hydrolysis, but it is also involved in the hydrolysis of other 2-monoacylglycerols and 1-monoacylglycerols. Its localisation is mainly presynaptic, where it often co-localises with CB1 receptors in the axon terminals. ABHD-6 and ABHD-12 belong to the α/β-hydrolase family with the postulated catalytic triad serine-aspartic acid-histidine. ABHD-6 is mainly post-synaptic where it regulates 2-AG levels at the site of its generation. This enzyme is also expressed in the mouse microglial cell line BV-2, in which monoacylglycerol lipase is not expressed. The ABHD-6 catalytic triad has not been resolved yet, but it is predicted to face the cytosol/intracellular membrane. ABHD-12 is highly expressed in microglia, macrophages and osteoclasts. Its catalytic triad is not resolved yet but it is predicted to face the luminal/extracellular side. Inactivating ABHD-12 mutations have been causally linked to neurodegenerative conditions, known as polyneuropathy, hearing loss, ataxia, retinitis pigmentosa and cataract.

Fig. 2. Schematic representation of anandamide and 2-arachidonoyl-glycerol metabolic routes. HETE, hydroxyeicosatetraenoic acid; HPETE-G, hydroxyperoxyeicosatetraenoylethanolamide; LOX, lypoxygenase; COX, cyclooxygenase; FAAH, fatty acid amide hydrolase; MAGL, monoacylglycerol lipase; NAAA, N-acylethanolamine-hydrolysing acid amidase; ABHD, α/β-hydrolase domain.

Oxidation

Both endocannabinoids can also be metabolised by oxidation involving enzymes such as cytochrome P-450, cyclooxygenase-2 (COX-2) and by the 12- and 15-LOX. MAG lipase is a serine hydrolase belonging to the α/β-hydrolase superfamily, whose catalytic triad is composed of Ser122, Asp239 and His269. It was originally purified, and subsequently cloned from adipose tissue, and it is detected in both cytosol and membrane preparation. This enzyme accounts for about 80–85% of 2-AG hydrolysis, but it is also involved in the hydrolysis of other 2-monoacylglycerols and 1-monoacylglycerols. Its localisation is mainly presynaptic, where it often co-localises with CB1 receptors in the axon terminals. ABHD-6 and ABHD-12 belong to the α/β-hydrolase family with the postulated catalytic triad serine-aspartic acid-histidine. ABHD-6 is mainly post-synaptic where it regulates 2-AG levels at the site of its generation. This enzyme is also expressed in the mouse microglial cell line BV-2, in which monoacylglycerol lipase is not expressed. The ABHD-6 catalytic triad has not been resolved yet, but it is predicted to face the cytosol/intracellular membrane. ABHD-12 is highly expressed in microglia, macrophages and osteoclasts. Its catalytic triad is not resolved yet but it is predicted to face the luminal/extracellular side. Inactivating ABHD-12 mutations have been causally linked to neurodegenerative conditions, known as polyneuropathy, hearing loss, ataxia, retinitis pigmentosa and cataract.

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endogenous controllers that include signals released from the gastrointestinal tract after meals, such as ghrelin, cholecystokinin, and peptide YY, as well as signals more strictly related to metabolism, such as the circulating hormones insulin and leptin. All stimuli involved in feeding are centrally integrated by the hypothalamus, a brain area known to play an important role in homeostatic control, thus maintaining an adequate body weight. There is now convincing evidence that the endocannabinoid system is involved in the regulation of food intake and energy expenditure. This is supported by the following observations: (i) Δ⁹-tetrahydrocannabinol, the main psychotropic ingredient of Cannabis sativa, has been found to induce signs of hyperphagia by activating cannabinoid CB₁ receptors; (ii) cannabinoid CB₁ receptors are activated after brief food deprivation in a manner that increases the levels of orexigenic and anorexigenic mediators and induces food intake; (iii) the levels of endocannabinoids in the hypothalamus are higher in rodents deprived of food for several hours *ad libitum*; (iv) when directly injected into the hypothalamus or the nucleus accumbens shell, endocannabinoids induce food intake in satiated animals. The fact that all these effects are attenuated by CB₁ receptor antagonists strongly supports a role of the endocannabinoid system in the regulation of food intake. Accordingly, cannabinoid CB₁ receptors have been found to exert both central and peripheral effects on food intake and energy homoeostasis. In the central nervous system, cannabinoid CB₁ receptors have been found to be localized in the olfactory bulb, cortical regions (neocortex, piriform cortex, hippocampus and amygdala) and several parts of the basal ganglia, thalamic and hypothalamic nuclei, cerebellar cortex, brainstem nuclei as well as in areas involved in reward/reinforcement circuitry. Furthermore, cannabinoid CB₁ receptors have been found to co-localise with other receptors in the central nervous system whose activities are essential in the processes of feeding and satiety. For example, the dopaminergic system, which is involved in reward regulation, interacts with CB₁ receptors and co-localisation between dopamine receptors (D₁ and D₂) and CB₁ receptors was reported in mouse hippocampus (CB₁ and D₂), and striatum and olfactory tubercle (CB₁, D₁ and D₂). In addition, it has been found that cannabinoid CB₁ receptor antagonists, such as SR141716 (also known as rimonabant), AM251 or AM1387, suppress food intake and disrupt food-reinforced behaviour; that food-deprived CB₁−/− mice eat less than their wild-type littermates (SR141716 does not affect the food intake of these animals) and that levels of endocannabinoids are elevated in leptin-deficient mice and rats, suggesting that endocannabinoids form part of the leptin-regulated neural circuitry that is involved in appetite regulation. In periphery, the endocannabinoid system acts directly to regulate processes such as gastric emptying, lipogenesis and glucose intake through cannabinoid receptors.
receptors expressed by peripheral cells and tissues controlling energy homeostasis, including the gut, the liver and hepatocytes, white adipose tissue, and adipocytes, skeletal muscle and the pancreas\(^{92}\). In this way, signals from these peripheral organs can be collectively converged and fed back centrally, allowing the brain to constantly monitor the metabolic state of an organism\(^{93}\).

**Endocannabinoids in obesity**

Besides its role in the regulation of food intake, there is also evidence that the endocannabinoid system is overactivated and dysregulated in human obesity. Obesity is a pathological condition whose incidence continues to increase as a global nutrition and health problem. One of the key factors leading to obesity is a significant imbalance between energy intake and expenditure. In addition, the high amount of \(n\)-6 PUFA, such as linolenic acid and arachidonic acid, over the \(n\)-3 PUFA, in the Western diet has hugely contributed to the onset of obesity. Unfortunately, the mechanisms by which different fatty acids contribute to obesity are not well-understood yet and further research is needed. The involvement of the endocannabinoid system in obesity is supported by the following observations:

1. CB\(_1\) receptor antagonists are significantly more efficacious in reducing caloric intake and body weight in rodents with diet-induced or genetic obesity than in their respective lean controls\(^{95,98,99}\).
2. CB\(_1\) receptor antagonists are resistant to diet-induced obesity\(^{100,101}\), and this resistance is due to both an up-regulation of CB\(_1\) receptors and elevated endocannabinoid levels, which have been detected in the adipose tissue of obese compared with lean patients\(^{102,103}\).
3. Importantly, CB\(_1\) receptor antagonists show significant anti-obesity effects. Rimonabant, which is a CB\(_1\) receptor inverse agonist/antagonist, has been found in clinical trials to reduce food intake in both lean and obese rodents and to lower body weight both in experimental models of obesity and in clinical trials\(^{104}\).
4. (ii) to decrease fat intake as well as hunger ratings\(^{104}\), and (iii) to improve waist circumference, plasma TAG, HDL cholesterol and blood pressure\(^{104}\).

Rimonabant was approved in 2006 as a weight loss medication in the European Union. Unfortunately, however, the use of this drug in the clinic has been suspended because of serious psychiatric side effects, particularly an increased incidence of depression and suicidality.

In this regard, the use of CB\(_1\) receptor antagonists that do not cross the blood–brain barrier might provide a novel pharmacological approach to controlling obesity without the psychiatric side effects observed with rimonabant and its analogues. In addition, the development of an ‘neutral’ CB\(_1\) antagonists, that do not show any significant signs of inverse agonism, has provided very promising results at the preclinical level, particularly in terms of their reversal of insulin and leptin resistance\(^{105}\).

Furthermore, in the light of the fact that the increased endocannabinoid tone in obesity might be to use DAGL inhibitors with consequent reduction in 2-AG biosynthesis\(^{106}\). Finally, changes in diet can be beneficial in preventing the onset of both obesity and other metabolic disorders. Indeed, several data reported in the literature suggest that dietary intake can modulate the endocannabinoid system. Thus, high-fat diets increase intestinal motility and the levels of the endocannabinoids, probably due to decreased monoacylglycerol lipase and FAAH activity and increased NAPE-phospholipase D action\(^{107}\). Importantly, the role of dietary fish oil \(n\)-3 fatty acids, EPA and DHA, in modulating endocannabinoid biosynthesis has been widely studied. Indeed, increased intake of EPA and DHA, that are able to displace arachidonic acid from phospholipid membranes, not only contributes to a marked decrease in endocannabinoid biosynthesis, but also causes a decrease in NAPE-phospholipase D, FAAH and CB\(_1\) mRNA expression with a consequent reduction of receptor stimulation\(^{107}\). However, such a change in diet should be considered with caution in newborn since it can cause long-lasting alterations in brain phospholipid composition and function\(^{105}\).

### Conclusions and future directions

It is now generally accepted that the endocannabinoid system plays a crucial role in several physiological processes and pathological conditions in both central and peripheral tissues. One challenge now is to develop:

1. (a) new peripherally restricted CB\(_1\) receptor agonists and/or antagonists that while maintaining the sought-after therapeutic effect do not show the unwanted side-effects that have been observed with direct CB\(_1\) ligands which cross the blood–brain barrier; (b) new medicines that affect the tissue level of endocannabinoids at their receptors for the treatment of a range of disorders, such as, to mention just a few, pain, multiple sclerosis, hypertension and cancer.

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### Conflicts of Interest

None.
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