SYMPOSIUM REVIEW

Does modulation of the endocannabinoid system have potential therapeutic utility in cerebellar ataxia?

G. J. Stephens

School of Pharmacy, University of Reading, Reading RG6 6AJ, UK

Abstract  Cerebellar ataxias represent a spectrum of disorders which are, however, linked by common symptoms of motor incoordination and typically associated with deficiency in Purkinje cell firing activity and, often, degeneration. Cerebellar ataxias currently lack a curative agent. The endocannabinoid (eCB) system includes eCB compounds and their associated metabolic enzymes, together with cannabinoid receptors, predominantly the cannabinoid CB₁ receptor (CB₁R) in the cerebellum; activation of this system in the cerebellar cortex is associated with deficits in motor coordination characteristic of ataxia, effects which can be prevented by CB₁R antagonists.

Gary Stephens  held postdoctoral and Fellowship positions with Wyeth Research, Imperial College and University College London before moving to University of Reading in 2005, where he is now Professor of Pharmacology and Director of Pharmacology and Therapeutics. His research interests are in the modulation of presynaptic calcium channels and G protein-coupled receptors, with a particular interest in cerebellar function.

This review was presented at the symposium “Mechanisms of cerebellar ataxias and neurodegeneration”, which took place at Ageing and Degeneration: A Physiological Perspective in Edinburgh, UK, 10–11 April 2015.

© 2016 The Authors. The Journal of Physiology published by John Wiley & Sons Ltd on behalf of The Physiological Society

DOI: 10.1113/jp271106

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.
Of further interest are various findings that CB1R deficits may also induce a progressive ataxic phenotype. Together these studies suggest that motor coordination is reliant on maintaining the correct balance in eCB system signalling. Recent work also demonstrates deficient cannabinoid signalling in the mouse ‘ducky’ model of ataxia. In light of these points, the potential mechanisms whereby cannabinoids may modulate the eCB system to ameliorate dysfunction associated with cerebellar ataxias are considered.

Cerebellar ataxias are a diverse group of disorders lacking a therapeutic agent

Cerebellar ataxias comprise a group of progressive neurological diseases associated with deficits in motor coordination and are typically associated with dysfunction and/or degeneration of Purkinje cells (PCs), the sole efferent output of the cerebellar cortex. There are a range of acquired ataxias and different hereditary forms of the disease (Klockgether, 2011). Thus, ataxia can be acquired from, amongst others, traumatic head injury, bacterial infection (meningitis or encephalitis), viral infection (chickenpox or measles), disruption of blood flow (stroke or transient ischaemic attack, haemorrhage), CNS disease (cerebral palsy or multiple sclerosis), sustained long-term alcohol misuse, under-active thyroid gland and cancer autoimmune conditions (lupus), and can also be iatrogenic. Hereditary ataxias may be autosomal-dominant diseases, including forms of spinocerebellar ataxia (SCA), several of which are associated with polyglutamine repeats in the dysfunctional protein; for example: ataxin 1 in SCA1; ataxin 2 in SCA2; Cacna1a encoding the voltage-dependent Ca$^{2+}$ channel (VDCC) CaV1.2.1 subunit in SCA6 (also in episodic ataxia 2). There are also autosomal-recessive diseases such as Friedreich’s ataxia and ataxia telangiectasia associated with deficits in, respectively, the mitochondrial protein frataxin and a serine/threonine protein kinase termed ataxia telangiectasia mutated protein (Klockgether, 2011). Despite this range of causes and implicated proteins, deleterious effects are largely limited to the cerebellar cortex and are typically associated with cerebellar dysfunction and/or degeneration and are manifest as motor incoordination. This commonality of symptoms offers hope for providing treatment options; however, at present there is no known cure for cerebellar ataxia. There are treatments to ameliorate associated symptoms. For example, vitamin E and anti-oxidants, such as co-enzyme Q10 and its synthetic analogue idebenone, have been suggested to have some benefit, largely in Friedreich ataxia. However, as yet, such agents lack proven efficacy in controlled clinical trials (Cooper et al. 2008; Lynch et al. 2010), although some improvement in comparison to controls was seen in cross-over trials,

(Received 14 June 2015; accepted after revision 4 February 2016; first published online 11 March 2016)
Corresponding authors G. J. Stephens: School of Pharmacy, University of Reading, Whiteknights, Reading RG6 6AJ, UK. Email: g.j.stephens@reading.ac.uk

Abstract figure legend Presynaptic CB1Rs modulate Purkinje cell output in the cerebellar cortex. Interneurons (INs) make inhibitory contacts predominantly at the so-called pinceau region surrounding the Purkinje cell (PC) soma and also potentially at dendritic shafts. Parallel fibres (PFs) arise from granule cells, which in turn receive input from mossy fibres, and make weak but numerous excitatory contacts predominantly with postsynaptic dendritic spines. Climbing fibres (CFs) arise from the inferior olive and make strong monosynaptic contacts with individual PCs within the dendritic tree, predominantly at dendritic shafts. 2-Arachidonoylglycerol (2-AG), the predominant endocannabinoid (eCB) in the cerebellar cortex, is synthesized from diacylglycerol (DAG) by diacylglycerol lipase (MAGL) localized predominantly to PF terminals. CB1Rs are ideally localized to the pinceau. CB1Rs are highly expressed at perisynaptic regions and also at extrasynaptic and synaptic PF sites, but at lower density on CF terminals. At all presynaptic terminals, CB1Rs predominantly couple to Gα1o to inhibit CaV1.2.1 Ca$^{2+}$ channels via release of Gβγ subunits (shown only at IN–PC synapses for clarity). Activation of presynaptic CB1Rs inhibits GABA release onto postsynaptic GABA$_A$ receptors and glutamate release predominantly onto postsynaptic AMPA receptors, respectively. As PCs represent the sole output of the cerebellar cortex, CB1Rs are ideally localized to control cerebellar function.

Abbreviations 2-AG, 2-arachidonoylglycerol; CBD, cannabidiol; CBDV, cannabidivarin; CF, climbing fibre; eCB, endocannabinoid; GPCR, G protein-coupled receptor; IN, interneuron; LTD, long term depression; MAGL, monoacylglycerol lipase; PC, Purkinje cell; pCB, phytocannabinoid; PF, parallel fibre; SCA, spinocerebellar ataxia; Δ9-THC, tetrahydrocannabinol; VDCC, voltage-dependent Ca$^{2+}$ channel.
suggesting that patients with vitamin E-deficient and co-enzyme Q10-deficient ataxia may receive some benefit (Cooper et al. 2008). In addition, administration of thyrotropin-releasing hormone (TRH) was reported to ameliorate cerebellar ataxia in rolling Nagoya mice (Shibusawa et al. 2008) and the TRH analogue taltirelin is approved to improve motor performance in ataxic patients in Japan.

The elucidation of function of proteins associated with inherited ataxias within the cerebellar cortex may also lead to future therapeutic advances relevant across different forms of ataxia. Amongst target proteins, the Cav2.1 (α1A) VDCC represents a widely studied protein. Cav2.1 subunits are highly expressed in the cerebellum (Westenbroek et al. 1995; Kulik et al. 2004). In particular, Cav2.1 is expressed postsynaptically in PCs (which led to the designation of these subunits as carriers of P-type Ca2+ current (Mintz et al. 1992)), at presynaptic terminals of inhibitory interneurons (INs) arising from basket and stellate cells, and of excitatory parvocellular fibres (PFs) and climbing fibres (CFs); such inputs regulate PC, and thus cerebellar cortex, output activity (Regehr & Mintz, 1994; Mintz et al. 1995; Stephens et al. 2001; Lonchamp et al. 2009). Several mouse Cav2.1 mutants display ataxia (Pietrobon, 2010; Rajakulendran et al. 2012). Correspondingly, genetic deletion of Cav2.1 is associated with a clear ataxic behavioural phenotype (Jun et al. 1999). Moreover, conditional PC-specific Cav2.1 knock-down was shown to be sufficient to induce impaired synaptic transmission and ataxia (Mark et al. 2011; Todorov et al. 2012), the former study termed their mice ‘purky’. Cell-specific work was extended to excitatory inputs into PCs, where it was shown that selective Cav2.1 knockdown in PFs (arising from mossy fibre inputs) in so-called ‘quirky’ mice, also gave rise to an ataxic phenotype (Maejima et al. 2013). Of further interest here, is that mutations which increase Cav2.1 current also give impaired synaptic transmission and irregular PC firing (a cerebellar epiphemone predicted to lead to motor incoordination) (Gao et al. 2012); these reports suggest that correct VDCC activity must be maintained for PC firing fidelity. To add to purky and quirky, we also have ‘duddy’ mice (Barclay et al. 2001). Ducky, and the related ducky2 (du2) strain, have mutations predicted to lead to deficits in α2δ-2 auxiliary VDCC subunit protein, which is expressed at high levels in normal cerebella (Cole et al. 2005) and is associated predominantly with Cav2.1 in the cerebellum (Barclay et al. 2001). In different ducky strains, the ataxic phenotype is associated with a reduction in postsynaptic PC whole-cell Ca2+ current (Brodbeck et al. 2002; Donato et al. 2006), together with irregular PC firing (Donato et al. 2006; Walter et al. 2006; Wang et al. 2013). Thus, several potential therapeutic targets have been suggested, largely confined to protein associated with inherited ataxias; however, as discussed above, as yet we have no cure for ataxia. The remainder of this review will focus on the potential to target the endocannabinoid (eCB) system to ameliorate cerebellar ataxia and, in particular, eCB compounds and their associated metabolic enzymes and G protein-coupled CB1Rs, one of the most ubiquitously expressed proteins in the mammalian cerebellum, and a protein which also modulates Cav2.1 activity at the presynapse.

Cannabinoid signalling and its potential links to cerebellar ataxia

Cannabinoids represent a diverse number of compounds, including (i) eCBs, for example, the lipid mediator 2-arachidonylglycerol (2-AG), which is the major eCB in the cerebellum (Szabo et al. 2006); (ii) plant-derived phytocannabinoids (pCBs), for example, the major herbal Cannabis constituents tetrahydrocannabinol (Δ9-THC) and cannabidiol (CBD) (Hill et al. 2012a); and (iii) exogenous synthetic agents, namely CB1R agonists, for example, WIN 55,212-2, an aminoalkylindole derivative, and CP 55940, which is structurally related to tetrahydrocannabinol, and CB1R antagonists/inverse agonists, for example, rimonabant (Pertwee et al. 2010), and newer allosteric modulators, for example, Org27569 (Price et al. 2005) and PSNCBM-1 (Horswill et al. 2007).

Within the CNS, cannabinoids predominantly activate CB1Rs, which represent the most widespread G protein-coupled receptor (GPCR) in the mammalian cerebellum (Herkenham et al. 1991; Tsou et al. 1997). CB1R expression is reported to be very low at PC cell bodies; rather, expression is high at excitatory PF inputs into PCs, reportedly with a presynaptic over extrasynaptic and synaptic localization, with lower CB1R expression at CF inputs onto PC dendritic shafts (Kawamura et al. 2006; see Abstract Figure). CB1R Rs are expressed at higher levels on presynaptic terminals of inhibitory INs, predominantly basket cells, but also stellate cells, which form a specialized region surrounding the PC axon initial segment known as the pinceau (the French word for paintbrush) (Tsou et al. 1997; Kawamura et al. 2006; Rodriguez-Cueto et al. 2014). Presynaptic CB1R Rs are activated by retrograde ‘on demand’ release of 2-AG from postsynaptic PCs. The major effect of presynaptic CB1R activation is a suppression of neurotransmitter release, whereby activation of presynaptic CB1R inhibits action potential-evoked and spontaneous inhibitory postsynaptic currents (IPSCs) at IN–PC synapses (see Fig. 1) or excitatory postsynaptic currents (EPSCs) at PF–PC and CF–PC synapses (Takahashi & Linden, 2000; Szabo et al. 2004; Kano et al. 2009). We have also used multi-electrode array recording to demonstrate that CB1R ligand-induced changes to cerebellar cortex network activity are mediated, at least in part, via effects on inhibitory synaptic transmission (Ma et al. 2008). CB1R activation has been
Figure 1. Presynaptic CB₁R modulation of inhibitory transmission at IN–PC synapses is deficient in ataxic ducky²J mice

Aa and Ba, representative spontaneous inhibitory postsynaptic current (sIPSC) traces from +/+ (Aa) and du²J/du²J (Ba) PCs showing effect of WIN55 (5 μM), and also subsequent application of AM251 (2 μM). Ab and Bb, summary bar graphs showing that WIN55 significantly reduced, and AM251 significantly increased, normalized sIPSC frequency in +/+ (Ab), but was without effect in du²J/du²J (Bb), conditions. *P < 0.05; **P < 0.01;
widespread with a number of different forms of short- and long-term synaptic plasticities which modulate cerebellar learning (Kano et al. 2009; Ohno-Shosaku & Kano, 2014). Thus, 2-AG release mediates the short-term suppression of inhibitory GABA release from IN terminals (depolarization-induced suppression of inhibition) or excitatory glutamate release (depolarization-induced suppression of excitation) (Szabo et al. 2006; Tanimura et al. 2009). Seminal work by Itô (1989) linked long term depression (LTD) by associative stimulation of PF and CF inputs to PCs, to motor learning in the cerebellum. It is also known that the metabotropic glutamate receptor 1 (mGlur1) pathway is critically involved in cerebellar development and LTD (Aiba et al. 1994), and it was further proposed that CF inputs into individual PCs were required for normal motor coordination (Chen et al. 1995). More recent work has established that cerebellar LTD is a post-synaptic phenomenon requiring 2-AG release from PCs and activation of presynaptic CB1Rs at PF–PC synapses (Safo & Regehr, 2005). Here, mGlur1 activation drives 2-AG release (Kano et al. 2009; see Abstract Figure). Thus, CB1Rs have a privileged position in the function and control of overall output of the cerebellar cortex and, as such, represent good potential targets to modulate dysfunctional signalling associated with cerebellar ataxias.

In cell lines and native neurons, CB1R activation causes pertussis toxin-sensitive inhibition of Ca2+/family VDCCs, and can also activate inwardly rectifier K+ channels (Mackie & Hille, 1992; Twitchell et al. 1997; Guo & Ikeda, 2004). It is likely that CB1Rs couple to presynaptic 2.1 (P/Q-type) VDCCs at IN–PC synapses to reduce action potential evoked GABA release (Forti et al. 2000; Stephens et al. 2001; Lonchamp et al. 2009) and to Ca2.1 (and to a lesser extent Ca2.2 and Ca2.3) at PF–PC synapses to reduce action potential-evoked glutamate release (Brown et al. 2004); these effects are most likely mediated by direct binding of G protein Gβγ subunits to VDCCs (Abstract Figure and Fig. 1).

CB1R agonists also cause clear reductions in frequency of ‘miniature’ IPSCs at IN–PC synapses (Takahashi & Linden, 2000; Yamasaki et al. 2006; Ma et al. 2008), consistent with an inhibition of action potential-independent GABA release. These effects are proposed to occur downstream of actions on voltage-dependent ion channels and are also consistent with direct effects on the synaptic release machinery, and also may be mediated by Gβγ subunits (Stephens, 2009). By contrast, CB1R agonist effects on miniature EPSCs at PF–PC synapses were only apparent when extracellular Ca2+ levels were increased (Yamasaki et al. 2006). Moreover, CB1R antagonists/inverse agonists such as AM251, rimonabant and the pCB Δ9-tetrahydrocannabinol all increase inhibitory GABA release at IN–PC synapses (Ma et al. 2008). Such effects are consistent with the presence of a strong, modulatable eCB tone in the cerebellum (Kreitzer et al. 2002; Galante & Diana, 2004), which provides further opportunity for therapeutic intervention in cerebellar ataxia.

Importantly, activation of presynaptic CB1Rs by synthetic cannabinoid and eCBs has been shown to promote cerebellar dysfunction, causing severe motor incoordination and modelling cerebellar ataxia (Lichtman et al. 1998; DeSanty & Dar, 2001; Patel & Hillard, 2001); in these studies pre-treatment with a CB1R antagonist or CB1R antisense prevented the induction of an ataxic phenotype. Such data suggest that CB1R antagonism may be useful in the pathogenic situation. In comparison to administration of CB1R ligands, data with CB1R knock-out mice are somewhat more equivocal. Thus, young/mature CB1R deficient mice are reported not to exhibit clear motor discoordination or changes to gait (Steiner et al. 1999; Kishimoto & Kano, 2006); however, deficits in motor function were reported in mature and older mice, in comparison to unaffected younger mice, in rotarod tests (Bilkei-Gorzo et al. 2005). One interpretation of these studies is that a progressive ataxic pathogenesis may be associated with long-term loss of CB1R. One common feature of CB1R knock-out mice, chronic marijuana users or animals administered CB1R agonists is a reported deficit in delay eyeblink conditioning, a cerebellar-dependent, motor learning process (Kishimoto & Kano, 2006; Skosnik et al. 2008; Steinmetz & Freeman, 2010). These data are consistent with CB1R controlling discrete motor function. Kishimoto & Kano (2006) also report that pharmacological block of CB1R had no effect on motor function in wild-type mice; however, it is also important to point out that CB1R deficiency and/or lack of effect of CB1R antagonism in a non-pathogenic situation does not preclude a role

---

repeated measurement one-way ANOVA followed by Tukey’s honest significant difference test. Ac and Bc, summary diagrams for +/- (Ac) and du2/dx2 (Bc) conditions. Ad, in wild-type conditions, CB1R activation (i.e. +WIN55) causes the release of Gβγ subunit from CB1R and subsequent inhibitory coupling of Gβγ to Ca2.1 at the presynapse to inhibit the action potential-evoked GABA release seen in control (CTL). Bd, by contrast, in du2/dx2 conditions, CB1R activation (i.e. +WIN55) has no effect on the GABA release seen in control (CTL). AM251 effects were also absent (see Wang et al. 2013). Thus, we propose that at synapses lacking α2δ-2 subunits (which associate predominantly with Ca2.1 in the cerebellum; Barclay et al. 2001), normal CB1R modulation of Ca2.1 is lacking. This deficit may relate to incorrect control of synaptic release by α2δ subunits (Hoppa et al. 2012); alternatively, it is possibly that lack of α2δ subunits may cause changes to CB1R-mediated G protein inhibition of Ca2.1.
in disease; for example, whilst SR141617A (rimonabant) reversed CB$_1$R-induced dysfunction, it had no effects itself on motor incoordination in non-ataxic animals (Lichtman et al. 1998; DeSanty & Dar, 2001). Together, these data suggest that CB$_1$Rs modulate cerebellar circuitry in ataxic disease, potentially with a progressive onset of effect. Therefore, targeting CB$_1$Rs may be beneficial in modulating motor incoordination in cerebellar ataxia, as discussed more fully below.

**An ataxic mouse model has deficient CB$_1$R signalling**

Whilst the role of ion channels (in particular, Ca$_{v}$2.1) has been broadly studied in animal models of ataxia, there has been much less work on the presynaptic receptors that modulate neurotransmitter release and the postsynaptic receptors responsible for onward signalling in such models. A study in Ca$_{v}$2.1 mutant tottering mice by Zhou and co-workers reported that presynaptic inhibition mediated by GABA$_{B}$ or a2-adrenoceptor GPCRs was enhanced at excitatory PF–PC synapses, although this may be as consequence of a switch to a reliance on Ca$_{v}$2.2 (N-type) channels for transmitter release (Zhou et al. 2003). Tottering mice also had a reduction in GABA$_{A}$ receptor expression, with specific deficits in granule cells (Kaja et al. 2007). We have shown that ataxic du2R mutant mice exhibit increased irregularity of PC and, to a lesser extent, granule cell firing in multi-electrode array recordings from cerebellar brain slices (Wang et al. 2013). Of note, clear effects on PC firing regularity in du2R/du2R mice were not seen in heterozygous +/-du2R mice, and the latter also lacked a clear behavioural ataxic phenotype. Importantly, the CB$_1$R-mediated inhibition at IN–PC synapses seen in litter-matched controls was completely absent in both +/-du2R and du2R/du2R mice. These data demonstrate that ataxic a2b2-2-deficient mice have aberrant presynaptic CB$_1$R-mediated signalling. The question arises as to whether deficiency in CB$_1$R-mediated signalling is involved in ataxia pathogenesis or whether it occurs as a result of the disease. It appears that, in this model, both alleles need to be affected in order for an ataxic phenotype to be seen (Wang et al. 2013), and thus progressive deficits may be associated with du2R mice. We saw no changes in PC firing regularity in response to CB$_1$R ligands in wild-type or du2R mice, consistent with a lack of postsynaptic CB$_1$R effects in this model. We propose that such deficits occur due to compromised Ca$^{2+}$ channel activity consequent to reduced presynaptic a2b2-2 expression in du2R mice (Fig. 1). In this regard, a2b2-2 subunits have been shown to be essential not only for Ca$^{2+}$ channel trafficking (Dolphin, 2012), but also for synaptic function, the latter by increasing transmitter release probability and also protecting release from inhibitory effects of intracellular Ca$^{2+}$ chelators (Hoppa et al. 2012).

There are few studies measuring CB$_1$R expression in ataxic animals; we reported no clear changes in expression in the cerebellar cortex of +/-du2R and du2R/du2R mice (Wang et al. 2013). In a recent study, post-mortem cerebellar tissue from patients with SCAs, CB$_1$R (and CB$_2$-R) expression was generally up-regulated in PCs, and also in glial cells (Rodriguez-Cueto et al. 2014a). Of interest here was that CB$_1$R expression was reported in PC soma and pinceau in SCA patients, but was confined largely to the pinceau in control patients. It is possible that upregulated postsynaptic CB$_1$R expression may affect 2-AG release in SCA patients; however, Rodriguez-Cueto and co-workers suggest that this CB$_1$R expression is associated with degenerating PCs and may represent a marker for degeneration and/or a protective response against such degeneration. A further study in SCA patients reported an up-regulation of eCB degradative fatty acid amidase hydrolase and monoacylglycerol lipase (MAGL) enzymes (Rodriguez-Cueto et al. 2014b), proposed to lead to reduced eCB levels in disease. In these studies, a compensatory up-regulation of cannabinoid receptor expression may occur as a consequence of reduced eCB levels; alternatively, it may be argued that eCBs are suppressed in order not to overactivate the system. Thus, it may also be possible to target eCB metabolizing enzymes for future therapeutic development. In this regard, potential avenues to increase 2-AG include inhibition of MAGL, localized predominantly to the PF terminal (Tanimura et al. 2012), or activation of the biosynthetic enzyme diacylglycerol lipase-$\alpha$ (DAGL$\alpha$) localized predominantly to the base of postsynaptic dendritic spines (Yoshida et al. 2006) (see Abstract Figure). It is also clear that we will need to investigate potential changes to eCB signalling in different animal models of ataxia to inform development of the most useful therapeutic strategies and also to determine if any such changes represent useful markers for different forms of ataxia.

**Do cannabinoids have therapeutic utility in cerebellar ataxia?**

There are anecdotal reports that cannabis smokers can achieve symptom relief for several CNS disorders. Such evidence has fuelled the investigation of use of CB$_1$R agonists as potential neuroprotective agents for a range of conditions including epilepsy, neurodegenerative diseases such as Alzheimer’s, Parkinson’s and Huntington’s disease and appetitive disorders (Fernández-Ruiz et al. 2011; Hill et al. 2012a). Earlier evidence for ataxia is largely confined to two case studies which suggest that oral $\Delta^{9}$-THC or marijuana improved motor coordination in some multiple sclerosis patients (Clifford, 1983; Meinek et al. 1989). At the clinical level, synthetic $\Delta^{9}$-THC has been used in management of nausea, emesis and pain, and nabiximols (Sativex) (containing $\sim$1:1 $\Delta^{9}$-THC:CBD)

© 2016 The Authors. The Journal of Physiology published by John Wiley & Sons Ltd on behalf of The Physiological Society
represents the first phytocannabinoid medicine, used as an oromucosal spray for pain and spasticity associated with multiple sclerosis (Hill et al. 2012a); Sativex was also stated to delay onset of ataxia symptoms in the Medicines and Healthcare products Regulatory Agency (MHRA) Public Information Report UK/H/961/01/DC. Such reports contributed to fuelling a major review on the clinical effects of cannabinoids in ataxia associated with multiple sclerosis (Mills et al. 2007); although cannabinoids showed promise, it was concluded that better standardized measures of ataxia were needed to fully establish the utility of cannabis-based medicines in ataxia. The role of cannabinoids in disease-associated movement disorders and tremor has been further discussed more recently by Arjmand et al. (2015) and Kluger et al. (2015), who similarly concluded that further work on cannabinoids in different models of ataxia is warranted. In this regard, an interesting recent report suggests that a ‘Sativex-like’ combination of δ9-THC and CBD, as well as the individual administration of Δ9-THC or CBD, was able to improve motor deficits in a viral model of multiple sclerosis (Feliú et al. 2015). Clearly, studies which suggest CB1R activation may be useful in cerebellar ataxia contrast to preclinical data where CB1R agonists induce an ataxic phenotype (Lichtman et al. 1998; DeSanty & Dar, 2001; Patel & Hillard, 2001); however, these data do support the hypothesis that maintaining the correct balance in eCB system signalling is a major factor for proper control of motor coordination. This hypothesis is further supported by data from Ca2+1 mutants described above, where both decreases (Maejima et al. 2013) and increases in Ca2+ current (Gao et al. 2012) can produce an ataxia phenotype; moreover, deficits in delay eyeblink conditioning are reported for both CB1R agonists and CB1R antagonists/inverse agonists using the same experimental design (Steinmetz & Freeman, 2010). CB1R agonists have also been shown to possess functional selectively or ‘biased agonism’, whereby different ligands (including eCBs) preferentially activate different CB1R signalling pathways (Laprairie et al. 2014; Khajehali et al. 2015). Whilst, as argued above, it is likely that CB1Rs act predominantly on presynaptic Ca2+1 to reduce transmitter release in the cerebellar cortex, alternative signalling pathways include inhibition of cAMP or stimulation of phosphorylation of signal regulated kinases (Howlett et al. 2010). Thus, it could be argued that by using knowledge of biased agonism that we can target specific pathways associated with diseases, including cerebellar ataxia. Finally here, CB1R agonists such as Δ9-THC have also been proposed to possess anti-oxidant (Hampson et al. 1998) and anti-inflammatory (although largely CB2R-mediated) (Fernández-Ruiz et al. 2011) properties; in common with other degenerative diseases, such properties may benefit the amelioration of cerebellar ataxia symptoms.

The demonstration that pre-treatment with a CB1R antagonist prevents the induction of motor incoordination by CB1R agonists (DeSanty & Dar, 2001; Patel & Hillard, 2001) suggests that CB1R antagonists/inverse agonists may be protective in ataxia. The archetypal agent rimonabant was introduced as an anti-obesity agent, but was withdrawn due to fears of increased suicidality and depression in patients (Nathan et al. 2011). Since then, therapeutic development of CB1R antagonists/inverse agonists has largely been put on hold. Interesting potential alternatives are CB1R negative allosteric antagonists, such as Org-27569 and PSNCBAM-1. These compounds have a somewhat unique pharmacological profile as they increase orthosteric agonist binding, but decrease agonist activity; more intriguingly, allosteric antagonist action is ligand-dependent and also shows biased antagonism for different signalling pathways (Baillie et al. 2013). We have shown that such functional selectivity for PSNCBAM-1 extends to effects on orthosteric ligands at IN–PC synapses in the cerebellar cortex (Wang et al. 2011); thus, PSNCBAM-1 attenuated CP55940 agonist and AM251 antagonist effects, but had no clear effects against WIN 55,212-2. Moreover, when applied alone, PSNCBAM-1 was not associated with potentially deleterious effects on eCB tone, a concern associated with use of CB1R antagonists/inverse agonists such as rimonabant. These studies indicate that exogenous allosteric CB1R ligands have potential to fine tune eCB orthosteric agonist effects in a ligand- and/or cell signalling-selective manner within the cerebellar cortex; moreover, biased antagonism effects may allow for further useful therapeutic development.

This review has focused on cannabinoids as agents acting on the eCB system in the cerebellum; moreover, the modulation of CB1Rs has been highlighted. It may transpire that, for exogenous compounds, targeting alternative modes of action offers improved therapeutic potential in diseases such as ataxia. The last few years have seen increasing calls for the use of medical marijuana to treat a range of disorders; of course, use of marijuana is intimately associated with psychoactive effects of the CB1R partial agonist Δ9-THC. Therapeutically, a more attractive option may be use of non-psychoactive pCBs. Thus, CBD and cannabidiivarinc (CBDV) have reported utility in epilepsy and, potentially, other CNS disorders (Hill et al. 2012b, 2013; Devinsky et al. 2014). The demonstration that Sativex can improve motor activity in multiple sclerosis (Feliú et al. 2015) is consistent with beneficial effects of a CB1R activator (Δ9-THC) in combination with CBD as a potential ameliorating agent for unwanted Δ9-THC effects (McPartland et al. 2015); for example, CBD alone was also effective in improving motor deficits, potentially via an action on peroxisome proliferator-activated receptor γ (PPARγ) receptors (Feliú
et al. 2015). In this regard, CBD has recently been awarded orphan drug status for the severe childhood epilepsy Dravet syndrome and is currently progressing well through clinical trials. CBD and CBDV have only low affinity at CB1Rs and CBD has been proposed, amongst other possibilities, to act at alternative GPCRs or at transient receptor potential ion channels or, possibly, to augment eCB tone via effects on metabolic enzymes (Hill et al. 2012a; McPartland et al. 2015). A recent study has proposed that CBD, as well as having CB1R-independent actions, may also act as a CB1R negative allosteric antagonist (Laprairie et al. 2015); therefore, CBD may share useful properties of this class of agents discussed above. It is also of interest that the hypoglycemic effects of the allosteric antagonist Org27569 have been suggested to occur independently of CB1Rs (Ding et al. 2014; Gamage et al. 2014). Thus, the use of cannabinoids with CB1R-independent and/or allosteric actions should also be considered.

In the future, it will be of interest in particular to test agents such as Sativex, and perhaps CBD as an individual compound, in cerebellar ataxia. There are a number of general points to consider, including whether deficits in CB1R-mediated signalling are hallmark characteristics of different forms of ataxia, how best to target such deficits and whether aberrant cannabinoergic signalling represents a useful biomarker for early or asymptomatic cerebellar ataxia. The answer to such questions will go some way to determining if modulation of the eCB system has therapeutic utility in cerebellar ataxia.

References

© 2016 The Authors. The Journal of Physiology published by John Wiley & Sons Ltd on behalf of The Physiological Society
The endocannabinoid system in cerebellar ataxia expression sets presynaptic calcium channel abundance receptor expression. In-vivo channel currents, altered cannabinoid α-receptors and their associated proteins. Proc Natl Acad Sci USA 1999, 204–215.


**Additional information**

**Competing interests**

The author has no conflict of interest.

**Funding**

Work in my group included here was supported by The Wellcome Trust and an Ataxia UK Postgraduate Fellowship awarded to Xiaowei Wang, who also received a University of Reading Postgraduate Research Studentship Award and was co-supervised by Prof. Benjamin Whalley. I also acknowledge the support of GW Pharmaceuticals in supplying material and associated grant funding during some of this work.