Realising the therapeutic potential of neuroactive steroid modulators of the GABA_A receptor

Delia Belelli^a, Derk Hogenkamp^b, Kelvin W. Gee^b, Jeremy J. Lambert^a,∗

^a Systems Medicine, Neuroscience, Mail Box 6, University of Dundee, Ninewells Hospital and Medical School, Dundee, DD1 9SY, United Kingdom
^b Department of Pharmacology, 110C Med Surge1, Mail Code 4625, University of California, Irvine, School of Medicine, Irvine, CA, 92697, USA

ARTICLE INFO

Keywords:
Allopregnanolone
GABA_A receptor
Neurosteroid
Phasic inhibition
Tonic inhibition

ABSTRACT

In the 1980s particular endogenous metabolites of progesterone and of deoxycorticosterone were revealed to be potent, efficacious, positive allosteric modulators (PAMs) of the GABA_A receptor (GABA_AR). These reports were followed by the discovery that such steroids may be synthesised not only in peripheral endocrine glands, but locally in the central nervous system (CNS), to potentially act as paracrine, or autocrine “neurosteroid” messengers, thereby fine tuning neuronal inhibition. These discoveries triggered enthusiasm to elucidate the physiological role of such neurosteroids and explore whether their levels may be perturbed in particular psychiatric and neurological disorders. In preclinical studies the GABA_AR-active steroids were shown to exhibit anxiolytic, anticonvulsant, analgesic and sedative properties and at relatively high doses to induce a state of general anaesthesia. Collectively, these findings encouraged efforts to investigate the therapeutic potential of neurosteroids and related synthetic analogues. However, following over 30 years of investigation, realising their possible medical potential has proved challenging. The recent FDA approval for the natural neurosteroid allopregnanolone (brexanolone) to treat postpartum depression (PPD) should trigger renewed enthusiasm for neurosteroid research. Here we focus on the influence of neuroactive steroids on GABA-ergic signalling and on the challenges faced in developing such steroids as anaesthetics, sedatives, analgesics, anticonvulsants, antidepressants and as treatments for neurodegenerative disorders.

1. Introduction

Almost 80 years ago Hans Selye demonstrated that particular pregnane steroids can induce rapid sedation and a state of unconsciousness (Selye, 1941). Approximately 40 years elapsed before a viable molecular mechanism emerged to explain these rapid behavioural effects. Electrophysiological studies revealed the intravenous synthetic steroidol general anesthetic alphaxalone (5α-pregnan-3α-ol-11, 20-dione) to enhance the inhibitory effects of GABA in guinea pig olfactory cortex (Scholfield, 1980) and in cat spinal cord neurons (Lodge and Anis, 1984). Extracellular recordings in the rat cuneate nucleus demonstrated alphaxalone to potently enhance responses mediated by GABA_A receptor (GABA_A R) agonists (Harrison and Simmonds, 1984). Supporting the GABA_A R as a locus for the behavioural effect, betaxalone, a 3β-ol isomer of alphaxalone, had no effect on GABA_A Rs and was behaviourally inert (Harrison and Simmonds, 1984). In their seminal paper they recalled that alphaxalone was structurally related to certain endogenous pregnane steroids, raising the prospect that the activity of the major inhibitory receptor in the mammalian central nervous system (CNS), the GABA_A R, may be subject to physiological, or pathophysiological regulation (Harrison and Simmonds, 1984). In confirmation, subsequent electrophysiological and radioligand binding approaches revealed particular metabolites of progesterone (e.g., 5α-pregnan-3α-ol-20-one, also known as allopregnanolone and now brexanolone) and of deoxycorticosterone (5α-pregnan-3α, 21-diol-20-one, [5α-THDOC]) to also be highly efficacious, stereoselective, positive allosteric modulators (PAMs) of the GABA_A R at nM concentrations (Majewska et al., 1986; Barker et al., 1987; Callaghan et al., 1987; Cottrell et al., 1987; Gee et al., 1988; Peters et al., 1988). Radioligand binding and electrophysiological studies established that the GABA facilitatory actions of these steroids were not mediated by binding to the proposed benzodiazepine site on the GABA_A R (Harrison and Simmonds, 1984; Cottrell et al., 1987; Gee et al., 1988). In common with barbiturates, these steroids promoted the open conducting state of the GABA_A R associated anion channel, thereby enhancing the actions of GABA and at higher concentrations, they directly activated the receptor (Majewska et al., 1986; Barker et al., 1987; Callaghan et al., 1987; Cottrell et al., 1987; Peters et al., 1988), leading

∗ Corresponding author.
E-mail address: jj.lambert@dundee.ac.uk (J.J. Lambert).

https://doi.org/10.1016/j.ynstr.2019.100207
Received 21 November 2019; Accepted 19 December 2019
Available online 23 December 2019
2352-2895/ © 2019 Published by Elsevier Inc. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ad</td>
<td>Alzheimer’s disease</td>
</tr>
<tr>
<td>allopregnanolone 5a-pregn-3α-ol-20-one</td>
<td></td>
</tr>
<tr>
<td>CNS</td>
<td>central nervous system</td>
</tr>
<tr>
<td>DGGCs</td>
<td>dentate gyrus granule cells</td>
</tr>
<tr>
<td>EEG</td>
<td>electroencephalogram</td>
</tr>
<tr>
<td>FDA</td>
<td>food and drug administration</td>
</tr>
<tr>
<td>GABA$_R$</td>
<td>GABA$_R$ receptor</td>
</tr>
<tr>
<td>HPA</td>
<td>hypothalamus, pituitary, adrenal axis</td>
</tr>
<tr>
<td>IPSC</td>
<td>inhibitory postsynaptic current</td>
</tr>
<tr>
<td>im</td>
<td>intramuscular</td>
</tr>
<tr>
<td>iv</td>
<td>intravenous</td>
</tr>
<tr>
<td>MOA</td>
<td>mechanism of action</td>
</tr>
<tr>
<td>nRT</td>
<td>nucleus reticularis</td>
</tr>
<tr>
<td>NREM</td>
<td>non rapid eye movement</td>
</tr>
<tr>
<td>ORG</td>
<td>ORG OD02-0</td>
</tr>
<tr>
<td>PAM</td>
<td>positive allosteric modulator</td>
</tr>
<tr>
<td>PD</td>
<td>pharmacodynamic</td>
</tr>
<tr>
<td>pGPCR</td>
<td>progestrone-G-protein coupled receptor</td>
</tr>
<tr>
<td>PK</td>
<td>pharmacokinetic</td>
</tr>
<tr>
<td>PKA</td>
<td>protein kinase A</td>
</tr>
<tr>
<td>PKC</td>
<td>protein kinase C</td>
</tr>
<tr>
<td>po</td>
<td>oral administration</td>
</tr>
<tr>
<td>PPD</td>
<td>postpartum depression</td>
</tr>
<tr>
<td>REM</td>
<td>rapid eye movement</td>
</tr>
<tr>
<td>SE</td>
<td>status epilepticus</td>
</tr>
<tr>
<td>VB</td>
<td>ventrobasal</td>
</tr>
</tbody>
</table>

GABA$_R$-active steroids. In agreement with previous studies (Belelli et al., 2009; Brickley and Mody, 2012) inspection of Table 1 reveals little GABA$_R$ isoform specificity of these steroids. Given this GABA$_R$ promiscuity a key question concerns the identification of the GABA$_R$ subtypes that mediate the behavioural repertoire neurosteroids. Experiments with “knock-in” mice genetically engineered to express diazepam-insensitive and etomidate-insensitive GABA$_R$s have revealed components of their behavioural effects to be mediated by particular GABA$_R$s (Rudolph and Knoflach, 2011). Key transmembrane amino acids have been identified that impair neurosteroid modulation of GABA$_R$s, permitting equivalent mouse behavioural studies, although to date there has not been a comprehensive behavioural profile of such mice (Newman et al., 2016). In the absence of such studies, components of the behavioural effects neuroactive steroids may exhibit a similar receptor profile to those of other GABA$_R$ modulators. However, whereas the effects of diazepam are mediated by enhancing the effects of GABA at γ-GABA$_R$s, importantly neurosteroids additionally act as PAMs of δ-GABA$_R$s. Indeed, behavioural studies of mice with deletion of the genes encoding for the δ subunit and the a4 subunit (often partnered with the δ subunit) are proving instructive (see below).

Receptors incorporating the γ2 subunit, are primarily, although not exclusively, expressed within inhibitory synapses, where they mediate fast phasic responses (under voltage-clamp conditions recorded as inhibitory postsynaptic currents [IPSCs]) upon activation by the neurally-evoked vesicular release of GABA (Farrant and Nusser, 2005; Brickley and Mody, 2012). In common, both benzodiazepines such as diazepam and neuroactive steroids prolong the IPSC duration, thereby enhancing phasic inhibition. Certain neurons (e.g. hippocampal dentate gyrus granule cells (DGGCs); thalamocortical ventrobasal [VB] neurons) additionally express neurosteroid-sensitive δ-GABA$_R$s (Brickley and Mody, 2012). These receptors are insensitive to benzodiazepines and are predominantly expressed out with the inhibitory synapse in perisynaptic, or extrasympathetic locations (Brickley and Mody, 2012). In these neurons extrasympathetic δ-GABA$_R$s mediate a tonic, persistent current, either in response to low ambient levels of GABA, or due to spontaneous gating of the receptor-channel complex (Brickley and Mody, 2012; Wlodarczyk et al., 2013). Neuroactive steroids, in common with GABA$_R$-active general anaesthetics, such as etomidate and propofol, will interact with synaptic γ2-GABA$_R$s to prolong the duration of phasic inhibition, but additionally with extrasympathetic δ-GABA$_R$s to increase tonic inhibition (Stell et al., 2003; Belelli and Lambert, 2005; Peden et al., 2008; Brickley and Mody, 2012) – Fig. 1. By contrast, benzodiazepines will primarily influence phasic inhibition, although certain neurons do express benzodiazepine-sensitive γ2 subunit containing GABA$_R$s (e.g. a5β2γ2), that mediate a tonic conductance (Caraiscos et al., 2004);

Considering how neurons respond during physiological rates of presynaptic stimulation, this division of fast phasic and tonic inhibition may be an over simplification. For example thalamocortical VB neurons...
Table 1
The potency and maximal efficacy of neuroactive steroids and non-steroidal modulators on the function of human GABA\(_{A}\)R subtypes expressed in Xenopus laevis oocytes. The GABA EC\(_{10}\) (the concentration of GABA that evokes a response 10% of the maximal response to GABA) was determined for each oocyte expressing the receptor subtype of interest. All compounds were tested with a 30 s pre-treatment prior to co-application with an EC\(_{10}\) concentration of GABA. The effect of the test drug upon the GABA EC\(_{10}\) response by the test drug was expressed as a percentage and calculated as: ([I GABA EC\(_{10}\) + modulator/I GABA EC\(_{10}\]) x 100), where I = current. The concentration-effect data were fitted to a four-parameter logistic equation (GraphPad Software, San Diego, CA). Data represent the mean ± S.E.M. (n = 3).\(^a\) Data from Hogenkamp et al. (2014) and Carter et al. (1997); AlloP = allopregnanolone; EC\(_{50}\) = the concentration of steroid producing half the maximum response of that compound. Max Mod = the maximum modulation of the GABA EC\(_{10}\) response produced by the test compound.

<table>
<thead>
<tr>
<th>Compound</th>
<th>GABA(_{A}) Receptor Subtype</th>
<th>EC(_{50}) ± SEM (μM)</th>
<th>Max Mod ± SEM (%) control</th>
<th>EC(_{50}) ± SEM (μM)</th>
<th>Max Mod ± SEM (%) control</th>
<th>EC(_{50}) ± SEM (μM)</th>
<th>Max Mod ± SEM (%) control</th>
<th>EC(_{50}) ± SEM (μM)</th>
<th>Max Mod ± SEM (%) control</th>
<th>EC(_{50}) ± SEM (μM)</th>
<th>Max Mod ± SEM (%) control</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlloP</td>
<td>α1β1γ2</td>
<td>0.09 ± .02</td>
<td>817 ± 62</td>
<td>0.11 ± 0.01</td>
<td>909 ± 68</td>
<td>0.27 ± 0.20</td>
<td>878 ± 211</td>
<td>0.11 ± 0.04</td>
<td>485 ± 257</td>
<td>0.54 ± .09</td>
<td>1401 ± 88</td>
</tr>
<tr>
<td>Ganaxolone</td>
<td>α1β1γ2</td>
<td>0.13 ± 0.04</td>
<td>1006 ± 241</td>
<td>0.79 ± 0.63</td>
<td>1151 ± 367</td>
<td>0.1 ± 0.06(^a)</td>
<td>700 ± 50(^a)</td>
<td>0.19 ± 0.07</td>
<td>646 ± 254</td>
<td>0.25 ± 0.06</td>
<td>1710 ± 534</td>
</tr>
<tr>
<td>UCI-50027</td>
<td>α1β1γ2</td>
<td>0.63 ± 0.05</td>
<td>472 ± 84</td>
<td>1.33 ± 0.25</td>
<td>587 ± 91</td>
<td>0.34 ± 0.18</td>
<td>277 ± 47</td>
<td>1.41 ± 0.47</td>
<td>595 ± 176</td>
<td>1.04 ± 0.45</td>
<td>919 ± 229</td>
</tr>
<tr>
<td>SAGE-217</td>
<td>α1β1γ2</td>
<td>0.08 ± 0.02</td>
<td>488 ± 33</td>
<td>0.32 ± 0.16</td>
<td>823 ± 353</td>
<td>0.18 ± 0.04</td>
<td>851 ± 93</td>
<td>0.38 ± 0.06</td>
<td>1355 ± 173</td>
<td>0.15 ± 0.03</td>
<td>763 ± 132</td>
</tr>
<tr>
<td>2–261</td>
<td>α1β1γ2</td>
<td>1.2 ± 0.5</td>
<td>24 ± 8</td>
<td>0.36 ± 0.02</td>
<td>1073 ± 194</td>
<td>0.95 ± 0.14</td>
<td>105 ± 33</td>
<td>0.16 ± 0.04</td>
<td>921 ± 47</td>
<td>0.45 ± 0.1</td>
<td>1771 ± 294</td>
</tr>
<tr>
<td>2–329</td>
<td>α1β1γ2</td>
<td>1.7 ± 0.2</td>
<td>843 ± 136</td>
<td>0.044 ± 0.003</td>
<td>947 ± 244</td>
<td>0.41 ± 0.07</td>
<td>1055 ± 322</td>
<td>0.018 ± 0.008</td>
<td>559 ± 151</td>
<td>0.14 ± 0.01</td>
<td>2775 ± 99</td>
</tr>
</tbody>
</table>
are innervated by GABA-ergic nucleus reticularis (nRT) neurons. Murine VB neurons express synaptic (α1β2γ2) and extrasynaptic (α4β2δ2) GABAARs, that mediate fast phasic and tonic inhibition respectively (Peden et al., 2008; Herd et al., 2013). During drowsiness and non-rapid eye movement (NREM) sleep these synaptic nRT neurons fire with high frequency bursts, consequently releasing substantial amounts of GABA onto VB neurons, which in addition to engaging synaptic GABAARs, spills over from the synapse to activate peri- and extrasynaptic GABAARs. Under voltage-clamp this spillover GABA results in a greatly prolonged IPSC. The slow component of the IPSC is absent in α4−/− mice and is prolonged by DS2, a GABAAR-selective PAM (Herd et al., 2013), confirming it to be mediated by activation of extrasynaptic GABAARs (α4β2δ2). For VB neurons allopregnanolone and related GABAAR-activating steroids greatly prolong fast phasic inhibition and increase the tonic current (Brown et al., 2015) – Fig. 1. Although the effects of neurosteroids on this spillover component of the IPSC remains to be determined, it is probable that allopregnanolone, in common with DS2 and atemodine (an intravenous general anesthetic), will greatly prolong such events (Herd et al., 2013, 2014). By contrast, benzodiazepines would be inert in this respect, causing only a relatively modest prolongation via the synaptic (α1β2γ2) component of the IPSC (Peden et al., 2008). Therefore, in some neurons the neurosteroid effect upon neural inhibition may be considerably greater than that of benzodiazepines (Weir et al., 2017).

A recent report highlights a further important, but indirect action of neurosteroids upon tonic inhibition (Parakala et al., 2019). In addition to binding to GABAARs, certain steroids, including allopregnanolone and progesterone activate a family of progesterone G-protein coupled receptors (p-GPCRs) located on the membrane surface (Pang et al., 2013; Schumacher et al., 2014; Parakala et al., 2019). The steroid ORG OD 02-0 (ORG) selectively activates these p-GPCRs, with no effect upon nuclear progesterone receptors and importantly, in contrast to allopregnanolone, has no direct interaction with GABAARs (Parakala et al., 2019). Activation of p-GPCRs by ORG has no immediate effect upon phasic, or tonic inhibition of dentate granule neurons. However, prolonged p-GPCR activation by this steroid produced a delayed, selective and sustained increase of the tonic current, due to an increased cell surface expression of extrasynaptic GABAARs, with no effect on phasic inhibition (Parakala et al., 2019). This metabotropic effect of ORG and allopregnanolone on GABAAR trafficking resulted from phosphorylation of particular serine residues of the GABAAR β3 subunit via an involvement of PKA and PKC (Parakala et al., 2019). Importantly, although the neuroactive steroid ganaxolone acutely increased the tonic current of hippocampal DGGNs, in contrast to allopregnanolone it did not produce a sustained enhancement of this conductance (Modgil et al., 2017).

In summary, allopregnanolone interacts directly with GABAARs to acutely prolong phasic and enhance tonic inhibition, but may exert an additional, metabotropic effect to increase tonic inhibition on a slower time scale, by selectively influencing extrasynaptic GABAAR trafficking. This form of sustained GABAAR plasticity may be important in understanding the therapeutic and physiological effects of allopregnanolone. In particular, it may underpin behavioural effects of allopregnanolone that remain following elimination of the steroid from the CNS. Highlighted by the differential profile of ganaxolone (Modgil et al., 2017), for future drug discovery programs, consideration of the activity of synthetic steroids upon the family of p-GPCRs may be warranted, in addition to the current focus on their direct interaction with the GABAAR. In certain neurons, including DGGNs, the extrasynaptic δ-GABAARs incorporate the β2 subunit (e.g. α4β2δ2) – (Peden et al., 2008; Herd et al., 2008). It will be of interest to explore if this metabotropic effect extends to such receptors (see Modgil et al., 2017). We will now consider attempts to develop neuroactive steroids as novel therapeutics, focussing primarily on inductions where the GABAAR is the likely site of action and where possible clinical findings are available for evaluation.

3. Developing clinical applications of neuroactive steroids

3.1. General anesthetics

The initial clinical use of neuroactive steroids was as general anesthetics. Following the discovery that progesterone exhibits both sedative and anticonvulsant efficacy in preclinical models (Selye, 1941), it was tested in humans intravenously (iv.) at 500 mg, a dose that produced an anesthetic effect (Merryman et al., 1954). This observation provided the impetus to examine the basis for this effect of progesterone and whether it had applications in developing new medicines. Based on pioneering work by Syntex on hypnotic steroids (Gyermek et al., 1968), in the 1970s Glaxo developed “Althesin” a combination of the steroids alphaxolone and alfaldalone (Child et al., 1971). These steroids are analogues of allopregnanolone, the former has an 11-carbonyl substitution and the latter an 11-carboxyl, 21-hydroxyl substitution. As described (Introduction), alphaxolone is an efficacious GABAAR PAM. Clinically, Althesin was tested as a potential iv. induction agent undergoing clinical trials in the United States in the 1970s, but did not receive FDA approval for this application, although it was approved by regulatory agencies in Europe.

Althesin was formulated in a surfactant polyethyalted castor oil (Cremophor). The attractive properties of Althesin, that distinguished it from other induction agents, were a lack of adverse cardiovascular, or respiratory effects, coupled with a limited post-recovery hangover due to a short half-life (Towler et al., 1982). However, Althesin caused anaphylaxis, resulting in withdrawal from human use, although it is used in veterinary practice (Barletta, 2019). The anaphylaxis was caused by histamine release induced by Cremophor and not the active components of Althesin (Johnson et al., 2011). An additional adverse effect of Althesin was hyperecxtability observed during induction and seizure activity during recovery (Towler et al., 1982). Minaxolone, a β1-ethoxy, 11α-dimethylamo substituted analogue of allopregnanolone was also developed, but never marketed (Kharasch and Hollmann, 2015). Organon improved upon the poor solubility by creating a series of water-soluble neuroactive steroids with anesthetic properties, which were highly efficacious GABAAR PAMs (Hill-Venning et al., 1996;
3.2. Sedatives

Satisfactory sleep is crucial for physical and mental health (Krause et al., 2017). Various neuropsychiatric disorders including depression and schizophrenia are accompanied by disrupted sleep architecture. Benzodiazepines and zolpidem are widely prescribed for sleep disorders, but their side effects, including tolerance and withdrawal, make them far from ideal (Wafford and Ebert, 2008). Investigations of sedative applications of the allopregnanolone-related steroids have been sporadic, despite sedation being their most apparent behavioural effect. Clinical trials of Althesin and alphaxalone revealed sedative effects (Ramsay et al., 1974; Stewart et al., 1983). Neuroactive steroids have desirable attributes at sedative doses including a short duration of action, no hangover, no effects on sleep architecture, limited effects on cognition and an absence of cardiovascular and respiratory depression (Towler et al., 1982).

Although the neuroactive steroids were described as “barbiturate like” (Harrison and Simmonds, 1984; Majewska et al., 1986) they were subsequently shown to act upon a distinct site on the GABA\textsubscript{A}R (Introduction). This finding opened a path to patent (US patent No. 5,120,723) to use the novel site on the GABA\textsubscript{A}R, by Gee and colleagues for the treatment of CNS disorders amenable to modulation by neuroactive steroids. This patent and others led to the development of synthetic neuroactive steroids related to allopregnanolone as drug candidates by CoCensys (Belelli et al., 1990; McNeil et al., 1992; Gee et al., 1995). They developed several orally bioavailable steroids for evaluation as sedative-hypnotics (Edgar et al., 1997; Vanover et al., 2001). In particular, CCD-3693, was more efficacious than benzodiazepines in promoting NREM sleep. In rats CCD-3693 did not interfere with rapid eye movement (REM) sleep and was more selective in reducing electroencephalogram (EEG) wakefulness, with less impairment of locomotor activity during waking than triazolam, or zolpidem (Edgar et al., 1997). In contrast to the benzodiazepines, neuroactive steroids do not produce a distinct “rebound” wakefulness following their NREM sleep-promoting effect. CCD-3693 was progressed into clinical development by CoCensys in collaboration with Searle in the 1990s, where it was not developed then because of pharmacoeconomic considerations.

Regarding mechanism, the sedative effects of the benzodiazepines are primarily mediated by \(\alpha1\beta2\) GABA\textsubscript{A}Rs (Wafford and Ebert, 2008; Rudolph and Knoflach, 2011) and neuroactive steroids are effective PAMs of such receptors (Table 1; Fig. 1). However, the sleep times induced by allopregnanolone and alphaxalone are reduced in \(\delta\) subunit mice, implicating extrasympathetic \(\delta\)-GABA\textsubscript{A}Rs (Mihalek et al., 1999).

Similarly, the sedative effects of gaboxadol, a \(\delta\)-GABA\textsubscript{A}R-selective agonist (Belelli et al., 2005) are impaired in \(\delta\) subunit mice (Boehm et al., 2006; Wafford and Ebert, 2008; Herd et al., 2009). Although these studies identify a credible target for developing steroid based sedatives, their poor oral bioavailability remains a major impediment.

3.3. Anticonvulsant

The demonstration that a single iv. infusion of Althesin suppressed seizures in 7 of 9 patients with status epilepticus (SE) provided the first clinical evidence that steroids related to allopregnanolone have anticonvulsant activity (Munari et al., 1979). Clearly a logical and obvious indication for allopregnanolone was epilepsy. In support, allopregnanolone exhibits anticonvulsant efficacy in a number of preclinical models of seizures (Belelli et al., 1989; Luntz-Leybman et al., 1990; Kokate et al., 1994, 1996; Devaud et al., 1995; Kaminski et al., 2004; Reddy and Rogawski, 2012; Wu and Burnham, 2018). However, neither Althesin, nor allopregnanolone, were viable as orally active anticonvulsants, having plasma half-lives of <1 h, limited solubility and oral bioavailability (Irwin et al., 2015). Side-stepping this impediment, a recent study described the successful treatment of two patients suffering from super-refractory SE following a two day continuous infusion with allopregnanolone (Vaitkevicius et al., 2017). Recently Sage Therapeutics, Inc. (Sage) took an i.v. formulation of allopregnanolone (brexanolone) into clinical testing for the treatment of drug refractory SE. The preparation, designated SAGE-547, showed promise in phase II trials, but failed to meet clinical endpoints in phase III (Rosenthal et al., 2017; Cox, 2017). Why SAGE-547 failed in phase III is not known. Perhaps the heterogeneous aetiology of SE undermines a response to the drug alone, or poor solubility prevented an optimal concentration from being achieved in the formulation used. Alternatively, a sustained allopregnanolone infusion may cause rapid PD tolerance (Turkmen et al., 2011). The clinical efficacy of allopregnanolone in large scale trials remains to be established in epilepsy, despite activity in preclinical models, or the anecdotal evidence of clinical activity of Althesin and other neuroactive steroids (Munari et al., 1979).

Ganaxolone, a synthetic analogue of allopregnanolone, was synthesised by CoCensys in the early 1990s to improve oral bioavailability, prevent in vivo conversion to progesterone and to increase the biological half-life (Carter et al., 1997). The introduction of a 3β-methyl group in ganaxolone significantly improved half-life, while retaining the GABA\textsubscript{A}R efficacy of allopregnanolone (Carter et al., 1997)—Table 1. This steroid was advanced by CoCensys into clinical trials in 1991 and showed promise as a potential antiepileptic (Reddy and Estes, 2016; Spirling et al., 2017). Ganaxolone was redirected for the treatment of acute migraine based on an uncertain rationale, but failed to demonstrate efficacy in phase II trials. Despite this costly detour, ganaxolone is currently under clinical development by Marinus Pharmaceuticals for treatment of various indications directed at seizure disorders, including cyclin-dependent kinase-like 5 deficiency disorder, protocadherin 19-related epilepsy and refractory SE (NCT03572933, NCT03865732, NCT03350035).

Recently, a series of novel (WO 2013/019711 A2) allopregnanolone-related steroids were designed to improve the aqueous solubility, bioavailability and side-effect profile of established neuroactive steroids and tested for antiepileptic activity (Hogenkamp et al., 2014). These 17β-heteroaryl steroids are represented by UCI-50027, the prototype in this series, 3-[3α-hydroxy-3β-methyl-5α-androstan-17β-yl]-5-(hydroxymethyl)isoxazole. UCI-50027 is an orally active anticonvulsant and anxiolytic, which overcomes the general dosing limitations of other neuroactive steroids. UCI-50027 has an improved preclinical pharmacokinetic (PK) and side-effect profile, which makes it more potent and tolerable as an anxiolytic and anticonvulsant than ganaxolone. For example, UCI-50027 has a greater anticonvulsant/anxiolytic therapeutic index than ganaxolone in rodent seizure models. Ganaxolone and UCI-50027 produce a robust enhancement of submaximal GABA-evoked currents in oocytes expressing human recombinant \(\alpha1\beta2\beta2\) and \(\alpha4\beta3\) GABA\textsubscript{A}Rs (Table 1). Both compounds are potent modulators of \(\alpha1\beta2\gamma2\) GABA\textsubscript{A}Rs, but whereas ganaxolone greatly enhanced the response to GABA irrespective of the β subunit isofrom, UCI-50027 produced only a relatively modest maximum modulation of \(\alpha2\beta2\gamma2\), c.f. \(\alpha2\beta2\gamma2\) GABA\textsubscript{A}Rs (Table 1). The differential influence of the β
subunit appeared selective for α2, but not the α1 subunit-containing GABAAR (Table 1). This reduced activity at the β1-subunit subtype may diminish the propensity to cause sedative/ataxic side effects in vivo at therapeutically relevant doses (Gee et al., 2010; Hogenkamp et al., 2014), although note the sedative effects of etomidate are mediated by GABAARs incorporating the β2-subunit (Reynolds et al., 2003).

Preclinical and clinical evidence suggests that allopregnanolone and related analogues should be useful in the treatment of various epilepsies, but to date none have received regulatory approval. Perhaps a more targeted approach, that requires a precise matching of the underlying pathophysiology of the various seizure disorders with the mechanism of action (MOA) of neurosteroids, may be a prerequisite for success. In that regard, numerous genetic mutations of GABAAR subunits, implying impairments to phasic and tonic inhibition, associate with particular epilepsies, including mutations of the δ-subunit (Macdonald et al., 2010). Some clinical anticonvulsants increase ambient levels of GABA, suggesting manipulations to influence tonic inhibition may be beneficial in certain conditions (Brickley and Mody, 2012). However, note that enhancement of tonic inhibition in models of absence epilepsy aggravates the condition by promoting thalamic burst firing (Cope et al., 2009; Errington et al., 2011).

3.4. Post-partum depression (PPD)

Blockade of neurosteroid production by inhibition of 5α-reductase with finasteride increases depression-like behaviors in experimental animal models (Walt et al., 2006; Beckley and Finn, 2007) and in some men treated for male pattern hair loss i.e. “finasteride syndrome” (Locci and Pinna, 2011; Melcangi et al., 2017). Allopregnanolone levels are negatively correlated with depression-like behaviors (Walt et al., 2006). Moreover, in humans antidepressant treatments increase allopregnanolone levels, which may be an integral component of their therapeutic effect (Romeo et al., 1998; Uzunova et al., 1998; Schule et al., 2007, 2011; Locci and Pinna, 2017). These findings are consistent with the documented role of the hypothalamus, pituitary, adrenal axis (HPA) dysfunction in the aetiology of depression (Lapin et al., 2009) and the dynamic regulation of neurosteroid levels in response to stressful experiences (Purdy et al., 1991; Tomaselli and Vallee, 2019) to influence HPA axis activity (Patchev et al., 1994; Gunn et al., 2015).

Mirroring changes in progesterone, allopregnanolone levels rise steadily through pregnancy until shortly before childbirth, when they begin to fall, with a steep decline occurring immediately after birth (Luisi et al., 2000; Gilbert Evans et al., 2005; Paoletti et al., 2006; Locci and Pinna, 2017). One hypothesis suggests enhanced allopregnanolone levels during pregnancy may reduce expression of extrasynaptic α4β3 GABAARs, which remain depressed among patients who develop PPD (Maguire and Mody, 2008; Licheri et al., 2015; Osborne et al., 2017). In support, homozygous (δ<sup>-/-</sup>) and heterozygous (δ<sup>+/+</sup>) mice, impaired in their ability to decrease and upregulate δ-GABAAR expression during pregnancy and postpartum respectively, developed depression-like and abnormal maternal behaviors, resulting in reduced pup survival (Maguire and Mody, 2008), although see Gunn et al. (2013). These symptoms were reversed in the heterozygous δ<sup>+/+</sup> mouse by the δ-GABAAR selective agonist gaboxadol (Maguire and Mody, 2008). If a similar dysregulation of receptor dynamics postpartum occurs in PPD then depressive symptoms may be exacerbated by fluctuating allopregnanolone levels and reduced δ-GABAAR expression.

Evidence relating perinatal mood and anxiety symptoms with absolute levels of allopregnanolone has been equivocal, especially in larger population studies. Reduced allopregnanolone levels are inversely correlated with depression scores in women during late pregnancy (Hellgren et al., 2014), but not in the second trimester (Hellgren et al., 2017). Interestingly, in this study a polymorphism in a gene involved in allopregnanolone synthesis, aldo-keto reductase family 1, which results in reduced allopregnanolone levels, was associated with an increase in depression scores. In another study second trimester cortisol, progesterone, pregnanolone and allopregnanolone levels were correlated with negative emotional symptoms (Crowley et al., 2016). Additional investigations demonstrated altered levels of GABA and neurosteroids in association with PPD (Deligiannidis et al., 2016). In contrast, mean allopregnanolone levels at 6 weeks postpartum in over 1500 ethnically diverse women showed no difference between healthy postpartum women and those with PPD (Guintivano et al., 2018). Low second trimester allopregnanolone levels were reported to predict subsequent PPD in a study of 60 pregnant women with mood disorders, where each additional ng/ml of this steroid reduced the probability of developing PPD by 63% (Osborne et al., 2017). However, there was no correlation when based on third trimester levels, consistent with another small study (Deligiannidis et al., 2013). It is not evident why levels during the third trimester showed no association. Studies reporting an association not with concurrent, but with subsequent symptoms, suggest that interactions with other systems, or other disease modifying changes (e.g., receptor plasticity, gene transcription/expression, or changes to rate-limiting enzymes - Agis-Balboa et al., 2014) and other pleiotropic events may contribute to the complex interactions between allopregnanolone and perinatal symptoms.

Regardless, recent treatment trials of the synthetic iv. formulation of allopregnanolone (brexanolone), in phase III trials on PPD resulted in a statistically significant difference in remission rates between placebo and two different doses of brexanolone (Meltzer-Brody et al., 2018). Although not new since CoCensys’ (U.S. patent No. 5,120,723, issued 1992) anticipated the use of allopregnanolone for PPD, Sage was awarded breakthrough status and FDA approval for brexanolone as the first drug approved specifically for PPD. The steady-state plasma levels of brexanolone based on the C<sub>min</sub> were in the 150–300 nM range during treatment infusion of PPD, corresponding to half the human EC<sub>50</sub> for enhancement of α4β3 GABAAR function by allopregnanolone (Brown et al., 2002). This magnitude of GABAAR facilitation would presumably be near maximal if the brain concentration is ×3 that in plasma, as observed in rodents (Irwin et al., 2015). Sage has rediscovered CoCensys’ neuroactive steroids with a follow-on compound to brexanolone, SAGE-217, a synthetic orally-active allopregnanolone analogue that is covered generically in CoCensys patents (U.S. 6,143,736 issued Nov. 7, 2000 and U.S. 6,277,838 issued Aug. 21, 2001). They reported positive results with the compound in their phase II study when tested at 30 mg p.o. (once a day for 14 days). In common with allopregnanolone, SAGE-217 is a potent PAM of recombinant receptors, representative of both synaptic (α1/2β1/2γ2δ) and extrasynaptic (α4γ3βδ) GABAARs (Table 1) – Martínez Botella et al. (2017). In agreement with this profile, for mouse thalamic VB neurons we find SAGE-217 (1 μM) to greatly prolong the duration of miniature inhibitory postsynaptic current events (mIPSCs) mediated synaptic (α1β2γ2δ) GABAARs and to enhance the tonic current mediated by extrasynaptic (α4γ2δ) GABAARs – Fig. 1.

Marinus is testing ganaxolone as an orally bioavailable treatment for PPD (NCT03228394, NCT03460756) with preliminary findings reported in the trade press as not meeting primary endpoints at an oral (p.o) dose of 1175 mg (once per day for 28 days). Given the similar GABAAR profile of these neuroactive steroids (Table 1) why is one steroid clinically active and the other inert? For example are they distinguished by their ability to activate the metabotropic progesterone receptor, leading to differences of δ-GABAAR trafficking (Modgil et al., 2017; Parakala et al., 2019)? Alternatively, the answer may reside in analysis of their pharmacokinetics, or other properties, revealed when these results are reported in peer-reviewed literature.

The intriguing possibility that neuroactive steroids have wider applications in clinical depression beyond PPD is now under investigation (Luscher and Mohler, 2019). A recent phase II study reported oral SAGE-217 treatment for 14 days to be effective in reducing depressive symptoms in patients with moderate to severe major depressive disorder (Gunduz-Bruce et al., 2019). The main side effects included dizziness and somnolence/sedation, not surprising given the GABAAR...
profile of this steroid (Table 1, Fig. 1).

If the apparent therapeutic effect is due primarily to acute facilitation of extrasynaptic δ-GABAAR function then other agents with a similar activity profile, may be useful in the treatment of PPD and other depressive disorders. Note benzodiazepines, which have no activity at δ-GABAARs, are not considered clinically useful in the treatment of depression per se (Baldwin et al., 2013), whereas clinically available drugs such propofol and etomidate, which in common with allopregnanolone, acutely enhance both phasic and tonic inhibition may be of interest (Beelli et al., 2005; Jia et al., 2007; Herd et al., 2013; Brown et al., 2015). However, note compounds such as propofol are unlikely to activate p-GPCRs to elicit a sustained effect upon δ-GABAAR-mediated tonic inhibition, distinguishing them from allopregnanolone (Abramian et al., 2014; Parakala et al., 2019).

Finally, studies investigating the impact of depressive disorders on not only levels of allopregnanolone, but on the steroid metabolism, may prove instructive and identify additional steroid targets (Sharp et al., 2018; Tomaselli and Vallee, 2019).

3.5. Analgesia

The thalamus is associated with the processing of nociceptive signals (Steriade and Deschenes, 1984; McCormick, 1992; Oliveras and Montagne-Clavel, 1994). Thalamic sensory relay neurons receive GABAergic projections from sensory nuclei and the thalamic reticular nucleus (Steriade and Deschenes, 1984; McCormick, 1992). Micro-injection of the GABAAR antagonist picrotoxin into the rat thalamic VB complex results in “pain-like” behavior (Oliveras and Montagne-Clavel, 1994). As discussed (Section 2), electrophysiological and immunohistochemistry studies reveal mouse VB neurons to express neurosteroid-sensitive synaptic (α1β2/3) and extrasynaptic (α4β2) GABAARs (Peden et al., 2008; Herd et al., 2013; Brown et al., 2015 – Fig. 1). Allopregnanolone is active in numerous models of acute and pathological pain states, with evidence of a neuroprotective effect (Kavaliers and Wiebe, 1987; Svensson et al., 2013; Borowicz et al., 2011; Rey and Coirini, 2015). The antinoceptive effects of allopregnanolone and ganaxolone are impaired in the δ−/− mice (Mihalek et al., 1999). The δ-GABAAR agonist gaboxadol is antinoceptive in rodents and humans (Reyes-Vazquez and Dafny, 1983; Grognet et al., 1983; Lindeburg et al., 1983; Kjaer and Nielsen, 1983), but analgesic efficacy is attenuated in the α4−/− mouse (Chandra et al., 2006). Collectively, these studies implicate extrasynaptic α4β8 GABAARs in mediating, or contributing to the antinoceptive effects of neuroactive steroids, possibly by enhancing thalamic burst firing (Cheong et al., 2008) and identify a putative target for the development of pain therapeutics (Whissell et al., 2015). Clinically, allopregnanolone and related analogues have not been evaluated for activity in pain states. The lack of reports on self-administration and tolerance to the analgesic effects of allopregnanolone related drugs, in contrast to opioids, makes them worthy of consideration as analgesics.

3.6. Alzheimer’s disease (AD) and neurodegenerative disorders

The role of allopregnanolone and related steroids in AD remains to be established as to whether it has a causal contribution, or is an epiphenomenon of the disease. It may be important to distinguish between the action of allopregnanolone as a PAM of the GABAAR versus actions at other sites (e.g., pregne X receptor, membrane bound p-GPCR – Section 2). In preclinical AD models allopregnanolone promotes neurogenesis, restores cognitive function and reduces pathology (Wang et al., 2010; Irwin et al., 2014; Ratner et al., 2019). The levels of allopregnanolone are reduced in the prefrontal cortex of AD patients (Marx et al., 2006). Perhaps GABAAR actions may contribute to the protective effects of allopregnanolone on neurodegeneration in AD models, but full efficacy may require a broader scope of interactions. However, the nature and extent of this contribution is unclear and may be minimal since ganaxolone (up to 30 mg/kg at 4 h post-injury) and pregnanolone (20 mg/kg) showed little effect in a preclinical model of cerebral hematoma, as measured by neurological and histological outcomes up to 3 months post-hematoma (Lyden et al., 2000). Additionally, progesterone failed to meet primary criteria in phase III clinical trials for the treatment of moderate to severe traumatic brain injury, although the contribution of allopregnanolone and related steroids, is unknown (Wright et al., 2014; Skolnick et al., 2014). Nevertheless, i.v. allopregnanolone has been tested in traumatic brain injury with equivocal results (NCT01673828).

Given the short metabolic half-life and absence of any reported PK/PD relationship at the GABAARs in various AD models of cognitive deficits, among the most compelling argument for its MOA is a pleiotropic effect of allopregnanolone and related steroids, perhaps including an action upon p-GPCRs to influence GABAAR expression (Parakala et al., 2019, Section 2). Allopregnanolone is currently in clinical trials for the treatment of mild cognitive impairment due to AD (NCT02221622). It was reported to be safe and well-tolerated in the 2–16 mg intramuscular (im.) range in a small blinded- and placebo-controlled trial of 24 patients (both male and female, age 55 and above), with mild cognitive impairment due to AD, or mild AD (Brinton et al., 2018). In this study the CogState battery scores showed high variability, with no significant differences in cognitive measures between groups, though scores trended towards improvement with treatment. Although anecdotal, MRI studies reported allopregnanolone (4 mg dose, intramuscular im.) to improve functional connectivity between the right parietal lobe and posterior cingulate cortex and to exhibit a sustained effect on hippocampal volume over the 3 weeks of treatment (Brinton et al., 2018). These encouraging preliminary results will require confirmation by larger trials to determine the validity of the drug target in AD. Interestingly, the acute administration of allopregnanolone and other GABAAR-active steroids to healthy subjects inhibits learning and memory function in a manner similar to the benzodiazepines (Bruins Slot et al., 1999; Johansson et al., 2002).

3.7. Beyond neurosteroids: non-steroid compounds selectively targeting α4β8 GABAAR subtypes

The clinical development of ganaxolone and allopregnanolone as drugs has relied on the use of patented formulations, which is driven by their poor physicochemical properties e.g. high lipophilicity (logP), which influences the bioavailability of the steroid. This major shortcoming is due to the intrinsic requirement of the androstane, or pregnane steroid core structure for efficacy (Hogenkamp et al., 2007). Although care is warranted regarding the interpretation of mouse gene deletion studies, the impaired behavioural efficacy of neuroactive steroids for either δ−/− or α4−/− mice identifyextrasynaptic α4β8 GABAARs as a target of interest in exploring the therapeutic potential of neuroactive steroids. As discussed (Section 2), the discovery that certain neuroactive steroids additionally activate p-GPCRs (Pang et al., 2013), leading to increased cell surface expression of δ-GABAARs (Parakala et al., 2019) may warrant determining the efficacy of novel steroids upon this target, in addition to profiling their effect upon GABAAR isoforms.

Alternatively, structural chemotypes with PAM activity at α4β8 GABAARs, but improved physicochemical properties can be evaluated for indications for which neurosteroids have potential and demonstrated therapeutic utility. Currently there are few non-steroidal, small molecules that are selective for δ-GABAAR subtypes. DS2 is a highly selective PAM for extrasynaptic δ-GABAARs, exhibiting no activity on synaptic GABAARs, but it has poor CNS penetration and was not dosed orally for pharmacological evaluation (Wafford et al., 2009; Jensen et al., 2013). Nevertheless, DS2 is reported to improve recovery in a mouse model of stroke by an anti-inflammatory mechanism (Neumann et al., 2019). AA29504 (Hoestgaard-Jensen et al., 2010), has a favorable ratio of brain to plasma levels, but was not dosed orally, nor is it a
pure PAM since it also has direct agonist activity (Vardy et al., 2012). Furthermore, as a carbamate, AA29504 may be too unstable to be absorbed through the gut after oral dosing. The selective δ-GABAA R agonist gadoxadol (in clinical development by Ovid Pharmaceuticals for treatment of Angelman and Fragile X syndromes) may worthy of consideration (Brown et al., 2002). However, the activity of δ-GABAA R PAMs are governed in part by physiological firing patterns (Section 2), whereas this is presumably less so for direct agonists such as gadoxadol (Herd et al., 2013; Weir et al., 2017).

The non-striatal small molecules 2–261 and 2–329 (Table 1), act as GABAA R PAMs via a binding site distinct from that of neurosteroids, or benzodiazepines (Gee et al., 2010). They compare favorably to the neurosteroids, including those currently in clinical development, in terms of potency, efficacy and selectivity for GABAA R subtypes including the δ3δ3 isoform (Table 1). They display unique pharmacological properties, which can be readily manipulated through their novel SAR to produce desirable side effects/profiles based on GABAA R receptor subunit-selectivity. For example, the orally bioavailable prototype, 2–261, retains anxiolytic activity without ataxia, cognitive impairment, ethanol potentiation, rewarding effects (linked to addiction), tolerance, or withdrawal (Gee et al., 2010; Yoshimura et al., 2014). Furthermore, in rodents 2–261 has a neurosteroid-like profile in blocking electrical- and chemical-kindled seizures and organophosphate-induced SE, and exhibits activity in chronic pain (Reddy et al., 2018; Johnstone et al., 2019a, b). Thus, retention of therapeutically desirable effects of the GABAA R-active steroids, but not their side effects, is clearly advantageous. The freedom to operate in the patent space provided by small molecules yields a more flexible approach to drug development, that builds upon the extensive body of knowledge accumulated during the last three decades on neuroactive steroids and GABAA Rs, but avoids their poor physicochemical properties and the prior art of the neurosteroid patent minefield.

CRediT author statement

Delia Beelli – Original writing, subsequent reviewing and editing.
Kelvin Gee - Original writing, subsequent reviewing and editing.
Derk Hogenkamp - Original writing, subsequent reviewing and editing.
Jeremy Lambert – Original writing, subsequent reviewing and editing.

References

Agis-Balboa, R.C., Guidotti, A., Pinna, G., 2014. 5α-reductase type I expression is downregulated in the prefrontal cortex/Brodmann's area 9 (BA9) of depressed patients. Psychopharmacology (Berl.) 233, 1299–1305.
Gee, K.W., Bolger, M.B., Brinton, R.E., Corini, H., McEwen, B.S., 1986. Steroid...


