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REVIEW

Minocycline: far beyond an antibiotic

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Minocycline is a second-generation, semi-synthetic tetracycline that has been in therapeutic use for over 30 years because of its antibiotic properties against both gram-positive and gram-negative bacteria. It is mainly used in the treatment of acne vulgaris and some sexually transmitted diseases. Recently, it has been reported that tetracyclines can exert a variety of biological actions that are independent of their anti-microbial activity, including anti-inflammatory and anti-apoptotic activities, and inhibition of proteolysis, angiogenesis and tumour metastasis. These findings specifically concern to minocycline as it has recently been found to have multiple non-antibiotic biological effects that are beneficial in experimental models of various diseases with an inflammatory basis, including dermatitis, periodontitis, atherosclerosis and autoimmune disorders such as rheumatoid arthritis and inflammatory bowel disease. Of note, minocycline has also emerged as the most effective tetracycline derivative at providing neuroprotection. This effect has been confirmed in experimental models of ischaemia, traumatic brain injury and neuropathic pain, and of several neurodegenerative conditions including Parkinson's disease, Huntington's disease, amyotrophic lateral sclerosis, Alzheimer's disease, multiple sclerosis and spinal cord injury. Moreover, other pre-clinical studies have shown its ability to inhibit malignant cell growth and activation and replication of human immunodeficiency virus, and to prevent bone resorption. Considering the above-mentioned findings, this review will cover the most important topics in the pharmacology of minocycline to date, supporting its evaluation as a new therapeutic approach for many of the diseases described herein.

Abbreviations

AIDS, acquired immunodeficiency syndrome; Aβ, amyloid β peptide; EAE, experimental autoimmune encephalomyelitis; eIF-2α, eukaryotic initiation translation factor-2 alpha; FDA, Food and Drug Administration; FXS, fragile X syndrome; HASMC, human aortic smooth muscle cell; HIV, human immunodeficiency virus; I/R, ischaemia-reperfusion; MHC, major histocompatibility complex; SCI, spinal cord injury; SIV, simian immunodeficiency virus; Th, helper T-cell; TLR, toll-like-receptor; VSMC, vascular smooth muscle cell

Introduction

Tetracyclines are bacteriostatic antibiotics that are considered broad-spectrum antibiotics because they are active against a wide range of aerobic and anaerobic gram-positive and gram-negative bacteria, and against other microorganisms, including *Rickettsia*, *Chlamydia* and *Plasmodium* spp., and *Mycoplasma pneumoniae* (Figure 1). The mechanism of action behind the antibiotic properties of tetracyclines is mainly related to their ability to bind to the bacterial 30S ribosomal subunit and inhibit protein synthesis. In an attempt to improve their efficacy, various structural changes have been employed, for example, ring D modification through carbons 7–9, which is the basis for the higher efficacy obtained with the semi-synthetic compounds minocycline and doxycycline (Nelson, 1998). Minocycline (7-dimethylamino-6-dimethyl-6-deoxytetracycline) is a second-generation, semi-synthetic tetracycline analogue that has been used for over 30 years (Yong *et al.*, 2004). It retains the efficacy against both gram-positive and gram-negative bacteria and has been approved by the Medicines and Healthcare Products Regulatory Agency for the treatment of acne vulgaris, and by the US Food and Drug Administration (FDA) for the treatment of some sexually transmitted diseases and rheumatoid arthritis (Good and

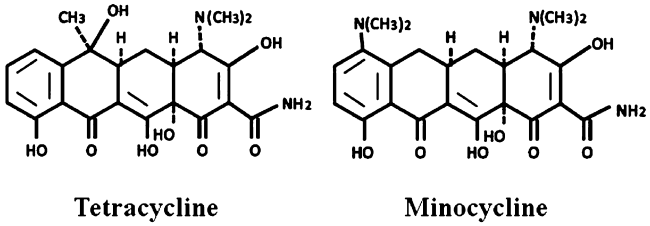

Figure 1

Chemical structure of minocycline and its parent, tetracycline.

Hussey, 2003; Blum *et al.*, 2004). Minocycline shows a better pharmacokinetic profile than the first-generation tetracyclines when used orally, being rapidly and completely absorbed, even in elderly populations, with a longer half-life and excellent tissue penetration, and an almost complete bioavailability (Barza *et al.*, 1975; Kramer *et al.*, 1978; Klein and Cunha, 1995). In addition, it is a highly lipophilic molecule that can easily pass through the blood–brain barrier (Brogden *et al.*, 1975), thus promoting its accumulation in cells of the CSF and CNS (Aronson, 1980; Yrjänheikki *et al.*, 1999; Kielian *et al.*, 2007) and enabling its use in the treatment of many CNS diseases (Saivin and Houin, 1988; Wang *et al.*, 2003; Yong *et al.*, 2004). Moreover, minocycline has a good safety record when used chronically. Long-term treatment with minocycline at dosages of up to 200 mg·day^{-1}, the highest dosage recommended by the US FDA, is generally safe and well-tolerated in humans. Minocycline's known and most common side effects, including nausea, vertigo and mild dizziness, occur mainly early after its administration and disappear shortly following therapy discontinuation. However, according to the British National Formulary, for treatments continued for more than 6 months, it is recommended to monitor every 3 months for hepatotoxicity, pigmentation and systemic lupus erythematosus, and it has been advised that treatment should be discontinued if these develop or if pre-existing systemic lupus erythematosus worsens. The higher risk of lupus-erythematosus-like syndrome and irreversible pigmentation associated with minocycline in comparison with other tetracyclines has limited its extensive use in human infections, being currently indicated just for the treatment of acne vulgaris (Williams *et al.*, 1974; Klein and Cunha, 1995).

The antibiotic properties of tetracyclines were initially described in the late 1940s; but more recently, numerous studies have focused on their non-antibiotic properties. In fact, it has been reported that tetracyclines can exert a variety of biological actions that are independent of their antimicrobial activity, including anti-inflammatory and anti-apoptotic activities, and inhibitory effects on proteolysis, angiogenesis and tumour metastasis (Golub *et al.*, 1991; 1992; Greenwald and Golub, 1993; Sapadin and Fleischmajer, 2006). This is the case for minocycline (Zemke and Majid, 2004; Kielian *et al.*, 2007), as it has recently been considered beneficial for diseases with an inflammatory basis, including rosacea, bullous dermatoses, neutrophilic diseases, pyoderma gangrenosum, sarcoidosis, aortic aneurysms, cancer metastasis, periodontitis and autoimmune disorders such as rheumatoid arthritis and scleroderma (reviewed in Sapadin and

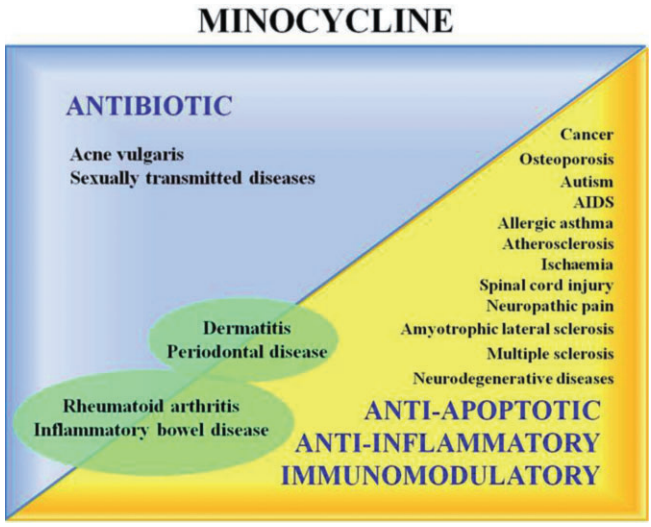

Figure 2

Clinical potential of minocycline due to its antibiotic activity; its anti-apoptotic, anti-inflammatory and immunomodulatory properties; and the association of both its non-antibiotic and anti-microbial effects.

Fleischmajer, 2006; Soory, 2008; Griffin *et al.*, 2010). Minocycline has also emerged as the most effective tetracycline derivative regarding neuroprotection, an effect that has been confirmed in experimental models of ischaemia (Yrjänheikki *et al.*, 1998; 1999; Koistinaho *et al.*, 2005), traumatic brain injury (Sanchez Mejia *et al.*, 2001) and neuropathic pain (Raghavendra *et al.*, 2003; Mei *et al.*, 2011), and of several neurodegenerative conditions such as Parkinson's (Du *et al.*, 2001; Thomas and Le, 2004; Abdel-Salam, 2008) and Huntington's (Chen *et al.*, 2000; Thomas *et al.*, 2004) diseases, amyotrophic lateral sclerosis (Zhu *et al.*, 2002), Alzheimer's disease (Choi *et al.*, 2007), multiple sclerosis (Brundula *et al.*, 2002; Nessler *et al.*, 2002) and spinal cord injury (SCI) (Golub *et al.*, 1991; Yong *et al.*, 2004; Festoff *et al.*, 2006). These preclinical studies have prompted the evaluation of minocycline in clinical trials in patients with neuronal disease, where it has shown promising neuroprotective properties (Lampl *et al.*, 2007). Moreover, the growing interest in minocycline has led to evaluations of its therapeutic efficacy in many other experimental disease models, such as inflammatory bowel disease (Huang *et al.*, 2009b; Garrido-Mesa *et al.*, 2011a,b), diabetes (Bain *et al.*, 1997; Wang *et al.*, 2003; Cai *et al.*, 2011), fragile X syndrome (FXS) (Paribello *et al.*, 2010), cardiac ischaemia (Scarabelli *et al.*, 2004) and human immunodeficiency virus (HIV) infection (Szeto *et al.*, 2010; Campbell *et al.*, 2011) (Figure 2).

Many of these studies have proposed the mechanisms that may be involved in minocycline's anti-inflammatory, immunomodulatory and neuroprotective effects. These include (i) inhibitory effects on the activities of key enzymes, like iNOS (Amin *et al.*, 1997), MMPs (Golub *et al.*, 1991) and PLA_2 (Pruzanski *et al.*, 1992); (ii) reduction of protein tyrosine nitration because of its peroxynitrite-scavenging properties (Whiteman and Halliwell, 1997); (iii) inhibition of caspase-1 and caspase-3 activation (Chen *et al.*, 2000); (iv) enhance-

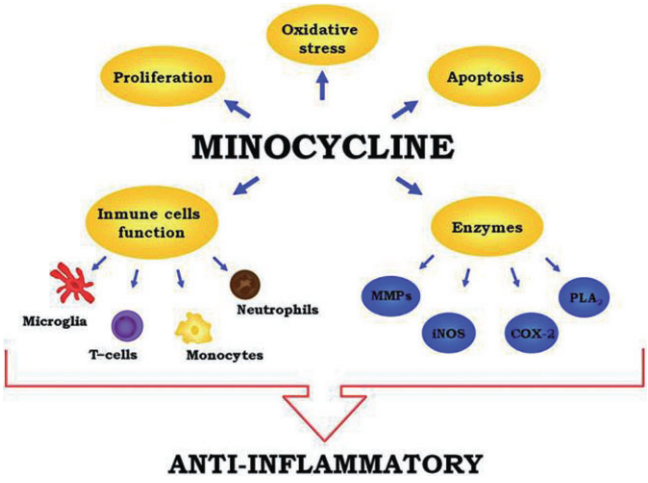

Figure 3

Mechanisms involved in the anti-inflammatory activity of minocycline: inhibitory effects on enzyme activities, like iNOS, MMPs, COX-2 or PLA_2; inhibition of apoptosis, through the inhibition of caspase-1 and caspase-3 activation and the enhancement of Bcl-2-derived effects; antioxidant properties and inhibition of immune cell activation and proliferation.

ment of Bcl-2-derived effects, thus protecting the cells against apoptosis (Wang *et al.*, 2003; Domercq and Matute, 2004; Jordan *et al.*, 2007); (v) reduction of p38 MAPK phosphorylation (Corbacella *et al.*, 2004); and (vi) inhibition of PARP-1 activity (Alano *et al.*, 2006). Tetracyclines' well-known ability of binding to Ca^{2+} and Mg^{2+} may account for some of these biological activities via the chelation of these cations and their transport into intracellular compartments (White and Pearce, 1982) (Figure 3).

In this review, we aim to summarize the effects reported for minocycline regarding its non-antibiotic properties in different experimental models, thereby supporting its evaluation as a new therapeutic approach for diseases associated with a deregulated immune response. This compound may have additional value in conditions in which an altered immune response and a microbial aetiology are involved, considering its ability to combine both immunomodulatory and anti-microbial properties.

Effects of minocycline on dermatitis

As tetracyclines, including minocycline, have been reported to reduce neutrophil chemotaxis (Esterly *et al.*, 1978; 1984), different studies have evaluated their effectiveness in cutaneous inflammation. Ishikawa *et al.* (2009) reported that minocycline, at concentrations similar to those obtained therapeutically in serum (5 or 10 μM) (Agwuh and MacGowan, 2006), reduced the protease-activated receptor 2-mediated production of IL-8, and thus attenuated the pro-inflammatory process in epidermal keratinocytes. They proposed that the ability of tetracyclines to chelate Ca^{2+} may contribute to these effects, as protease-activated receptor 2 activation transiently increases intracellular Ca^{2+} levels in keratinocytes, triggering the downstream binding of NF-κB to DNA (Macfarlane *et al.*, 2005; Stefansson *et al.*, 2008). Open clinical studies have confirmed minocycline's efficacy in non-infectious forms of dermatitis (Humbert *et al.*, 1991), supporting its clinical use in various skin disorders, such as inflammatory acne, rosacea, bullous dermatoses and neutrophilic dermatoses (Sapadin and Fleischmajer, 2006). Maintenance of remission in some of these conditions frequently required concomitant administration of corticosteroids; however, most of these reports were generally non-placebo-controlled or uncontrolled studies, and included small number of patients. Therefore, further evaluation of larger numbers of patients in randomized, well-controlled studies is still necessary. Finally, although minocycline is recommended for the aforementioned skin disorders, current therapy has moved towards the use of doxycycline, which has a similar efficacy for the treatment of these conditions with a reduced incidence of adverse effects, such as drug hypersensitivity syndrome, hyperpigmentation and dizziness, frequently associated with minocycline therapy (Bachelez *et al.*, 2001; Sapadin and Fleischmajer, 2006; Korting and Schöllmann, 2009).

Effects of minocycline on periodontal disease

The pharmacological profile of tetracyclines, which combines anti-microbial with anti-inflammatory and anti-apoptotic properties, makes them suitable for periodontal disease treatment, which is characterized by an inflammatory process in addition to its well-known microbial aetiology (Soory, 2008). At the levels conventionally detected in the plasma and gingival crevicular fluid, minocycline causes a significant stimulation of osteoblastic cells, whereas long-term exposure of these cells to tetracyclines results in a proportional increase in the mineralized bone matrix (Gomes and Fernandes, 2007). These effects are achieved without affecting the survival and protein expression of human gingival fibroblasts, epithelial cells and periodontal ligament fibroblasts (Suzuki *et al.*, 2006). Taken together with their anti-microbial activity, these effects may explain the efficacy, in particular of minocycline, in reducing disease progression and promoting periodontal healing when administered at doses of 100–200 $mg \cdot day^{-1}$ for 7–14 days (Kirkwood *et al.*, 2007; Basegmez *et al.*, 2011).

Effects on minocycline on rheumatoid arthritis

Because of the anti-collagenase activity of minocycline initially described by Golub *et al.* (1983), and later confirmed by Greenwald *et al.* (1987), in human rheumatoid tissue and synovial cultures, many studies over the last four decades have focused on its effects in rheumatoid arthritis. In the adjuvant arthritis model of rheumatoid arthritis, tetracyclines reduced collagenase activity in the inflamed tissue, although they did not show anti-inflammatory effects in rats (Greenwald *et al.*, 1992). When combined with non-steroidal

anti-inflammatory drugs in the same study, tetracyclines had a synergistic effect, as evidenced by a total inhibition of degradative enzyme activity and a normalization of radiological bone damage. Similarly, they were shown to inhibit the synthesis and/or activity of cartilage proteinases both *in vitro* and *in vivo* (Arsenis *et al*., 1992). In another study, Zernicke *et al*. (1997) reported that tetracycline derivatives could reverse the deleterious effects of adjuvant disease on the mechanical strength of the femur in rats. These studies led to clinical trials with different tetracyclines, including minocycline. Initially, two double-blind, placebo-controlled trials were conducted: one by Kloppenburg *et al*. (1994) and the minocycline in rheumatoid arthritis trial (Tilley *et al*., 1995). The former demonstrated that minocycline had clinically useful anti-inflammatory properties in patients with rheumatoid arthritis and was superior to the placebo, whereas no clear conclusions could be drawn from the latter. A few years later, Langevitz *et al*. (2000) summarized the results of two previous open trials and three double-blind controlled studies. They concluded that minocycline might be beneficial in patients with rheumatoid arthritis, especially when administered early in the course of the disease or in patients with only mild disease, showing beneficial effects with respect to joint swelling and/or tenderness, laboratory parameters and patient assessments. A meta-analysis from 2003 that summarized the results from the clinical trials conducted until 2002 confirmed these beneficial effects (Stone *et al*., 2003). Despite these promising results and the FDA approval of semi-synthetic tetracyclines for rheumatoid arthritis, in a recent review, Greenwald (2011) acknowledged that the weak anti-inflammatory properties of tetracyclines are easily surpassed by many other agents. Nevertheless, the potential of tetracyclines in osteoarthritis treatment still seems attractive and the *in vitro* inhibition of cartilage degradation by minocycline presents a solid rationale for forward progress.

Effects of minocycline on CNS pathologies

As previously mentioned, minocycline, because of its high lipid solubility (Good and Hussey, 2003), easily crosses the blood–brain barrier (Brogden *et al*., 1975; Saivin and Houin, 1988; Yong *et al*., 2004), and in recent years, has been shown to be beneficial in animal models of CNS diseases. Many of these studies were initially based on minocycline's ability to inhibit microglia activation, a process that has deleterious effects on neurogenesis and neuronal survival, which would justify its potential effectiveness in the treatment of neuroinflammatory and/or neurodegenerative disorders (Yrjänheikki *et al*., 1998; Chen *et al*., 2000; Du *et al*., 2001; Zhu *et al*., 2002; Metz *et al*., 2004; Tomás-Camardiel *et al*., 2004). In fact, different *in vitro* studies have described minocycline's ability to block LPS-stimulated inflammatory cytokine secretion and Toll-like-receptor (TLR)-2 surface expression in the BV-2 microglia-derived cell line and on microglia isolated from the brains of adult mice. Minocycline also attenuated the mRNA expression of inflammatory genes, including IL-6, IL-1β, major histocompatibility complex (MHC) II and TLR-2 (Nikodemova *et al*., 2006; Henry *et al*., 2008).

Minocycline's ability to mitigate cytokine expression in the brain during systemic inflammatory events may be useful in preventing cognitive and behavioural deficits. Indeed, minocycline attenuates sickness behaviour and anhedonia associated with LPS-induced neuroinflammation, in parallel with a decrease in neuroinflammatory markers in the hippocampus and cortex and in indolamine 2,3-dioxygenase (IDO) mRNA expression (Henry *et al*., 2008). These data are consistent with those from another report showing a causal relationship between IDO activity and acute depressive effects in adult CD-1 mice. In that report, minocycline's ability to block IDO induction prevented depressive-like immobility (O'Connor *et al*., 2009). In addition, the authors observed that, while minocycline pre-treatment attenuated LPS-induced brain IL-1β production, it had no effect on plasma IL-1β levels, suggesting that minocycline has anti-inflammatory effects within the brain, which accounts for the recovery from sickness and the reduction in the frequency of neurobehavioural complications.

Consistent with its anti-inflammatory properties, minocycline has been reported to act as a neuroprotective agent in models of both global and focal ischaemia, processes driven by the infiltration of the ischaemic brain area by inflammatory cells (Feuerstein *et al*., 1997; Koistinaho and Hökfelt, 1997). In a gerbil model of forebrain ischaemia, minocycline prevented microglial activation, reducing the infarct size and increasing the survival of hippocampal neurons, even when treatment began after the ischaemic insult. These effects were accompanied by a reduction of IL-1β-converting enzyme, COX-2 and iNOS mRNA levels in the affected brain regions (Yrjänheikki *et al*., 1998; 1999). Koistinaho *et al*. (2005) showed that this effect of minocycline seemed to be MMP-dependent, as this compound protected against permanent cerebral ischaemia in wild-type mice, but not in MMP-9-deficient mice. Moreover, Park *et al*. (2011) reported that minocycline, similar to other MMP inhibitors, was effective in treating neuroinflammation following experimental photothrombotic cortical ischaemia. In those studies, both pre- and post-ischaemic minocycline treatment significantly reduced the infarct size and the expression of neuroinflammatory mediators in the ischaemic cortex, confirming previous reports (Romanic *et al*., 1998; Koistinaho *et al*., 2005) and clearly attributing this effect to MMP inhibition.

Reduction in the expression of inflammatory mediators within the brain after minocycline treatment has been repeatedly reported in pre-clinical studies, accounting for its inhibitory effects on infarct size in ischaemia models and positive effects on behavioural complications associated with neuroinflammatory processes. Given these promising experimental results, translational research is required to provide new insights into the usefulness of minocycline in these CNS pathologies.

The potential efficacy of minocycline in the treatment of Parkinson's, Alzheimer's and Huntington's diseases has been proposed. Chen *et al*. (2000) evaluated minocycline's effects in the transgenic R6/2 mouse model of Huntington's disease and reported that minocycline delayed disease progression and mortality. The mechanism was determined to be inhibition of caspase-1 and caspase-3 expression, and reduction of iNOS activation, preventing the detrimental effect that these enzymes exert in Huntington's disease (Ona *et al*., 1999).

Moreover, minocycline-treated mice showed significantly inhibited generation of the endogenous Huntington cleavage fragment and lower mature IL-1β levels in the brain. The anti-inflammatory effects of minocycline may also account for the beneficial effects observed in both *in vitro* and in animal models of Parkinson's disease. Minocycline was found to prevent nigrostriatal dopaminergic neurodegeneration in the 1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine (MPTP) mouse model of Parkinson's disease, an effect related to the prevention of dopamine depletion in the striatum and nucleus accumbens, and is associated with marked reductions in iNOS and caspase-1 expression (Du *et al.*, 2001). In a different study, minocycline's ability to protect nigrostriatal dopaminergic neurons was related to reduced MPTP-induced activation of microglia, inhibition of mature IL-1β formation, and NADPH oxidase and iNOS activation (Wu *et al.*, 2002). In addition, *in vitro* studies using primary cultures of mesencephalic and cerebellar granule neurons (CGN) and glia confirmed that minocycline inhibited 1-methyl-4-phenylpyridinium (MPP+)-mediated iNOS expression and NO-induced neurotoxicity. This effect was related to the inhibition of p38 MAPK activation in CGN (Du *et al.*, 2001). Together, these results suggest that minocycline blocks MPTP neurotoxicity *in vivo* by indirectly inhibiting MPTP/MPP+-induced glial iNOS expression and neurotoxicity, most likely by inhibiting the phosphorylation of p38 MAPK. In contrast to these promising results, minocycline's ineffectiveness and/or deleterious effects have also been reported in studies on animal models of Huntington's (Diguet *et al.*, 2003; 2004a; Smith *et al.*, 2003) and Parkinson's (Yang *et al.*, 2003; Diguet *et al.*, 2004a) diseases. Therefore, minocycline seems to have variable and even contradictory effects in different species and models of these neurological disorders. Could these discrepancies be due to differences in the mode of administration and dose used? Additional experimental work should be undertaken to determine whether minocycline has a neuroprotective effect in Huntington's and Parkinson's diseases before conducting further clinical trials (Diguet *et al.*, 2004b).

In view of the pathogenesis of amyotrophic lateral sclerosis, which has been related to up-regulation of the expression and the increased activity of different pro-inflammatory signals, including caspase-1, caspase-3, iNOS and p38 MAPK (Friedlander *et al.*, 1997; Li *et al.*, 2000), there is also a rationale for minocycline to be beneficial in this disease. Indeed, minocycline delayed disease onset and extended survival in an experimental model of amyotrophic lateral sclerosis-transgenic mice expressing the mutant human SOD1-G93A transgene. In this model, minocycline inhibited mitochondrial permeability transition-mediated cytochrome *c* release, a mechanism of action that was confirmed *in vitro* both in cells and in isolated mitochondria (Zhu *et al.*, 2002). Similar findings were reported by Kriz *et al.* (2002) and Van Den Bosch *et al.* (2002), who showed that minocycline delayed the onset of motor neuron degeneration and muscle strength decline and increased the longevity of amyotrophic lateral sclerosis mice. Additional *in vitro* studies revealed that minocycline reduced the apoptosis of cultured neurons from patients with motor neuron diseases, including amyotrophic lateral sclerosis (Tikka *et al.*, 2002). As is the case for Huntington's and Parkinson's diseases, the usefulness of minocycline in this neurological condition remains controversial, however. Despite the promising results from these animal models, a multi-centre, randomized placebo-controlled phase III trial revealed minocycline to have a detrimental effect. Amyotrophic lateral sclerosis patients treated with the drug deteriorated significantly faster than patients in the control group (Gordon *et al.*, 2007).

Pre-clinical studies have confirmed that minocycline's pharmacological profile could be of interest in the treatment of Alzheimer's disease. The first report describing the effects of minocycline in a model of Alzheimer's disease appeared in 2004, describing the drug's beneficial effects in an experimental Alzheimer's disease model induced by i.c.v. injection of μ-p75-saporin in mice. Minocycline ameliorated cholinergic cell loss and reduced the simultaneous activation of microglia and astrocytes that occur after the administration of the immunotoxin, and led to the down-regulation of transcription of pro-inflammatory mediators and mitigation of cognitive impairment (Hunter *et al.*, 2004). Minocycline treatment has also been reported to suppress microglial production of IL-1β, IL-6, TNF and nerve growth factor in amyloid precursor protein (APP) transgenic mice, but did not affect amyloid β peptide (Aβ) deposition in this model (Seabrook *et al.*, 2006). Moreover, Choi *et al.* (2007) reported that minocycline could attenuate the phosphorylation of eukaryotic initiation translation factor 2 alpha (eIF-2α), which may ultimately impair cognitive functions by decreasing the efficacy of the *de novo* protein synthesis required for synaptic plasticity (Harding *et al.*, 2000; Chen *et al.*, 2003; Taylor *et al.*, 2005) and caspase-12 activation, in $A\beta_{1-42}$-treated or C-terminal fragments of APP (APP-CTs)-transfected differentiated PC 12 neuronal cells. The increases in p-eIF2a were also attenuated by minocycline administration in two animal models: $A\beta_{1-42}$ infused rats and Tg2576 mice, in which minocycline reduced neuronal cell death, improved cognitive impairment and attenuated the deficits in learning and memory (Choi *et al.*, 2007). Similarly, minocycline treatment was able to correct behavioural impairments and lower levels of inflammatory markers and Aβ trimers in an early, pre-plaque inflammatory process in an Alzheimer's disease-like transgenic rat model (Cuello *et al.*, 2010). Aβ accumulation was sufficient to induce cognitive impairment and biochemical alterations in the cerebral cortex and hippocampus in the absence of amyloid plaques, together with up-regulation of pro-inflammatory markers, such as MHC II, iNOS and COX-2, and these responses were successfully arrested by minocycline (Cuello *et al.*, 2010). Thus, minocycline treatment ameliorates the cognitive impairment and deficits in learning and memory that characterize Alzheimer's disease by a variety of actions, and future work must aim to determine its usefulness in patients.

Finally, and more importantly, increasing experimental evidence suggests that minocycline, alone or combined with other drugs, could ameliorate multiple sclerosis severity and progression. This finding has been derived mainly on the basis of the promising results obtained in an established animal model of multiple sclerosis, the experimental autoimmune encephalomyelitis (EAE). In 2002, two different groups described minocycline's ability to attenuate the clinical and histological severity of EAE, an effect associated with decreased inflammation and the inhibition of microglial acti-

vation (Brundula *et al.*, 2002; Popovic *et al.*, 2002). Popovic *et al.* (2002) reported that minocycline administration, following a curative protocol, suppressed ongoing disease activity and limited disease progression in EAE induced in dark agouti rats. Similarly, Brundula *et al.* (2002) showed that minocycline, most probably because of its ability to inhibit MMP activity, delayed the onset of clinical symptoms and attenuated the severity of the neuroinflammation that occurred in EAE, even when it was administered after the onset of the clinical signs. Later, Nikodemova *et al.* (2007) reported that minocycline treatment, when started at the onset of the symptoms, considerably decreased the severity of the clinical course of the disease by reducing both lesion number and size. This effect was associated with a reduced macrophage migration from the periphery into the CNS, thus resulting in decreased leukocyte infiltration into the parenchyma of the spinal cord and decreased microglia MHC II expression and proliferation. Moreover, these neuroprotective effects were improved when high minocycline concentrations were locally delivered into the CNS (Xue *et al.*, 2010).

Minocycline was also effective in combination with atorvastatin, a statin previously reported to be effective in attenuating clinical EAE in mice (Youssef *et al.*, 2002). Combination therapy caused greater reduction in disease severity than individual drugs used alone, in both acute and chronic disease phases, along with attenuation of inflammation, demyelination and axonal loss (Luccarini *et al.*, 2008).

The mechanisms responsible for the pharmacological actions of minocycline in EAE are its influence on T-cell activity, its ability to inhibit microglial activation and its neuroprotective effects. *In vitro* studies have revealed that minocycline inhibited antigen processing for presentation to human T-cells (Kalish and Koujak, 2004), T-cell proliferation and production of inflammatory cytokines (Kloppenburg *et al.*, 1995; 1996), and T-cell transmigration across a fibronectin matrix barrier, most likely via the inhibition of MMPs. *In vivo* assays have found that this antibiotic promotes immune differentiation from a type 1 helper T-cell (Th1) to a type 2 helper T-cell (Th2) phenotype, thus modulating the susceptibility to EAE (Popovic *et al.*, 2002). Regarding microglial activation, Popovic *et al.* (2002) found in relapsing-remitting EAE that activated microglia were absent in rats treated with minocycline. Moreover, minocycline inhibited microglia MHC II expression and the subsequent reactivation of T-cells, which resulted in attenuation of the clinical severity of EAE (Nikodemova *et al.*, 2007) and reduced infiltration of T lymphocytes into the CNS parenchyma (Brundula *et al.*, 2002; Popovic *et al.*, 2002). In addition, the direct antioxidant potential of minocycline attenuated reactive oxygen species (ROS)-mediated neuronal and axonal destruction *in vitro* (Wilkins *et al.*, 2004) and its ability to chelate Ca^{2+} may prevent the activation of calpains and preserve axonal integrity, as observed in minocycline-treated EAE rats (Stirling, 2004; Yong *et al.*, 2004; Maier *et al.*, 2007). The success of minocycline in multiple sclerosis treatment in experimental models prompted its evaluation in phase I/II clinical trials in humans. These confirmed its beneficial effects and found it to be safe and well-tolerated (Metz *et al.*, 2004; 2009; Zabad *et al.*, 2007). The results revealed that minocycline significantly reduced relapse rates, MRI – active lesions, and local brain atrophy. The trials also showed that the clinical response to minocycline was accompanied by beneficial immune changes that may be desirable in the control of multiple sclerosis. Therefore, of all the neurological conditions considered here, it appears that minocycline has the most potential in the treatment of multiple sclerosis. Strong experimental evidence supports minocycline's ability to reduce the severity and progression of the disease, which has been confirmed by the clinical trials performed to date. Phase III clinical trials should be conducted to determine the drug's potential for multiple sclerosis treatment.

Effects of minocycline on neuropathic pain

The contribution of glial cells to the initiation of neuropathic pain sensitization and peripheral nerve injury-induced neuropathic pain has been well-characterized (Inoue and Tsuda, 2009; Zhuo *et al.*, 2011). As mentioned earlier, minocycline inhibits microglial activation in various pathological conditions, without affecting astroglia and neurons (Yrjänheikki *et al.*, 1998 ; Tikka *et al.*, 2001), and this may justify its reported ability to reverse neuronal sensitization in neuropathic animal models when applied to the spinal cord (Tikka *et al.*, 2001; Raghavendra *et al.*, 2003). In fact, several studies have revealed that minocycline can exert anti-nociceptive effects on experimental neuropathic pain induced by peripheral nerve injury, inflammation or SCI, after both systemic (i.p.) and local (intrathecal) administration (Raghavendra *et al.*, 2003; Hains and Waxman, 2006; Owolabi and Saab, 2006; Mika *et al.*, 2007). Minocycline's beneficial effects in these cases are clearly enhanced when it is administered as early as possible, especially during the initiation stage (Ledeboer *et al.*, 2005; Owolabi and Saab, 2006; Mei *et al.*, 2011). Similarly, minocycline has been recently found to reverse microglial reactivity and thermal hyperalgesia secondary to sciatic neuropathy when injected into the ventral posterolateral thalamus (LeBlanc *et al.*, 2011). Special attention has been given to minocycline's effects in the development of diabetic neuropathy. Pabreja *et al.* (2011) recently reported that the chronic administration of minocycline significantly prevented cold allodynia and thermal hyperalgesia in diabetic rats. This beneficial effect was associated with decreased levels of pro-inflammatory cytokines and an attenuated oxidative stress balance in the spinal cord of these diabetic animals. Moreover, the beneficial effects of minocycline in diabetes were associated with the prevention of retinal complications, most probably because of the inhibition of diabetes-induced cytokine and cytotoxin production (Krady *et al.*, 2005). Consistent with this finding, Wang *et al.* (2005) showed that minocycline inhibited the up-regulation and increased release of IL-1β, TNFα and NO caused by bacterial LPS in retinal microglia. Cai *et al.* (2011) investigated the neuroprotective mechanisms of minocycline against diabetic brain injury and reported its ability to improve the behavioural deficits caused by altered glucose metabolism in diabetic rats. In addition, they demonstrated that the drug down-regulates the increased Aβ in the hippocampus by inhibiting signal transduction molecules upstream of the NF-κB pathway and by attenuating oxidative stress. The anti-

nociceptive effects of minocycline have subsequently been confirmed in different models of neuropathic pain (spinal nerve transection, peripheral nerve injury, inflammation, sciatic neuropathy and SCI), particularly when it was administered during the initiation stage, and have been attributed to the inhibition of microglia activation. In diabetes, in addition to the amelioration of diabetic neuropathy, minocycline prevented retinal complications and improved behavioural deficits. Human trials have not yet been conducted, but based on the available experimental data, minocycline therapy seems like a rational approach for these conditions.

Effects of minocycline on SCI

Because the neuropathic pain and motor weakness that result from microglia activation are believed to trigger nociceptive hypersensitivity in SCI, minocycline could be a rational approach for treating the complications of this condition (Colburn *et al.*, 1999). Support for this proposition comes from the results of different studies that show that minocycline may reduce neuropathic pain after SCI. However, few data exist regarding minocycline's ability to promote motor recovery after SCI, rendering this possibility controversial. In rodent models of SCI, minocycline administration significantly improved both hindlimb function and strength, reduced the gross lesion size in the spinal cord and induced axonal sparing. Minocycline-treated mice demonstrated superior behavioural recovery than that shown by methylprednisolone-treated mice, the approved treatment for acute SCI in humans (Wells *et al.*, 2003). In rats with SCI, minocycline inhibited the release of cytochrome *c* from the mitochondria, markedly enhancing long-term hindlimb locomotion (Teng *et al.*, 2004). More recently, Saganová *et al.* (2008) showed that both short- and long-term treatment with minocycline had a neuroprotective effect on the spinal cord rostral to the injury epicentre. Previous data had indicated that minocycline exerts a protective effect on white matter and motor neuron number at sites both rostral, but also caudal, to the lesion epicentre (Teng *et al.*, 2004).

Minocycline has also been shown to improve functional recovery after SCI through the inhibition of pro-nerve growth factor production by microglia, thereby reducing oligodendrocyte death and apoptosis after traumatic SCI. It also inhibited the expression of p75 neurotrophin receptors and the activation of the Ras homolog gene family member A (RhoA) after SCI (Yune *et al.*, 2007). Furthermore, Festoff *et al.* (2006) reported that minocycline might also exert a neuroprotective effect in SCI by reducing microgliosis and inhibiting caspase expression. A recent study reported minocycline's effects on motor neuron recovery and neuropathic pain in a rat model of thoracic SCI (Cho *et al.*, 2011). The study revealed that, at post-operative day 2, the locomotor score was higher and mechanical hyperalgesia was reduced in minocycline-treated animals than in the corresponding controls. The attenuation of neuropathic pain behaviour and motor recovery correlated with reductions in microglia and astrocyte activation respectively. Experimental data have subsequently clarified that minocycline could be of benefit in SCI in different ways: relieving pain and promoting motor recovery after lesion development. However, clinical studies evaluating its potential application in human SCI are still missing.

Effects of minocycline on ischaemia

Minocycline's ability to limit tissue damage in the kidney, heart, lung and neural cells in the setting of ischaemia both *in vitro* and *in vivo* has been documented (Yong *et al.*, 2004; Stirling *et al.*, 2005; Sutton *et al.*, 2005; Jordan *et al.*, 2007). When considering stroke, blood–brain barrier disruption after stroke can worsen ischaemic injury by increasing oedema and causing haemorrhage. Minocycline, probably because of its ability to inhibit microglia activation, was able to attenuate infarct volume and neurological deficits in mice after experimental stroke, as a result of a marked reduction in blood–brain barrier disruption and haemorrhage (Yenari *et al.*, 2006). Based on this preliminary evidence, clinical studies in patients with stroke have been performed. Lampl *et al.* (2007) reported that the oral administration of minocycline (200 mg) for 5 days, with a therapeutic window of 6–24 h after stroke onset, promoted a better outcome compared with the placebo. This beneficial effect could be associated with significant blunting of ischaemic tissue oxidative stress, consistent with previous reports (Kraus *et al.*, 2005). In another ischaemic condition, the myocardial ischaemia-reperfusion (I/R) injury, in which the damage has been associated with the activation of MMPs and serine proteases, minocycline exerted a protective effect, as confirmed by various pre-clinical studies. The evaluation in *ex vivo* heart systems and cultured cardiac myocytes revealed minocycline's ability to affect apoptotic cell pathways (Scarabelli *et al.*, 2004). Various *in vivo* studies have also described the cardioprotective effects of minocycline, as antibiotic pre- and post-treatment of rats subjected to I/R resulted in a significant reduction in infarct size, an effect that was accompanied by a reduction in MMP-9 activity and oxidative stress (Romero-Perez *et al.*, 2008). These assays confirmed previous results that the accumulation of tetracyclines in infarcted myocardium was directly related to the degree of tissue damage (Holman *et al.*, 1973; Holman and Zweiman, 1975). In fact, the levels of minocycline that accumulated in the myocardium were several fold higher than those in the plasma, with increased accumulation in ischaemic compared with normal myocardium. Thus, it is possible that some of the cardioprotective effects of minocycline may be attributable to its high tissue levels, which allow for notable effects on its targets: MMP-9 inhibition and ROS-scavenging, together with anti-apoptotic effects. In a more recent study, the protective effect of minocycline against myocardial ischaemia and I/R injury was also attributed to inhibition of the expression of high mobility group box 1 (HMGB1), a protein that has been also found to act as an early mediator of inflammation and cell damage during I/R injury (Andrassy *et al.*, 2008; Hu *et al.*, 2010). PARP-1 inhibition has also been proposed as a possible mechanism underlying minocycline's cardioprotective activity (Tao *et al.*, 2010). During myocardial I/R injury, there is an increase in reactive oxygen and nitrogen species that leads to oxidative DNA damage and the activation of nuclear repair enzymes, such as PARP-1, which promote DNA repair under normal conditions, but which

could lead to cell death if excessive (Zhang and Niu, 1994; Yu *et al.*, 2002; Alano *et al.*, 2006). In cultured adult rat cardiac myocytes in which I/R injury was simulated using oxygen-glucose deprivation, minocycline, at micromolar concentrations, significantly reduced cell death and biochemical markers of PARP-1 activation and prevented mitochondrial permeability transition (Tao *et al.*, 2010). Moreover, minocycline has also been reported to be effective in preventing ischaemia-induced ventricular arrhythmias in rats. The incidence of ventricular fibrillation, the duration and the number of episodes of ventricular tachycardia plus unidentifiable and low-voltage QRS complexes, and the severity of arrhythmias were significantly reduced by minocycline treatment (Hu *et al.*, 2011). In that study, the authors postulated that the anti-arrhythmic effect of minocycline may have been associated with activation of the PI3K/Akt signalling pathway and mitochondrial K_{ATP} channels, which are known to participate in the anti-arrhythmic effect of ischaemic or pharmacological preconditioning during myocardial ischaemia (Végh and Parratt, 2002; Gourine *et al.*, 2005). Similar clinical benefits of minocycline as those shown in stroke patients could be expected in myocardial ischaemia patients, especially considering its cardiotropisms, antioxidant properties and cardioprotective activity shown in experimental models, *in vitro* and *in vivo*.

Effects of minocycline on atherosclerosis

Various studies have proposed minocycline to prevent atherosclerosis, in relation to its cytoprotective effects in vascular cells. Accordingly, minocycline has been shown to protect against diabetic microvascular complications (Krady *et al.*, 2005) and to reduce neointima formation in macrovascular disease following acute vascular injury of the rat carotid artery (Pinney *et al.*, 2003). In these studies, a reduction in the number of vascular smooth muscle cells (VSMC) was seen after minocycline treatment, which was attributed to an inhibition of MMP activity and cytokine-induced VSMC migration (Pinney *et al.*, 2003; Yao *et al.*, 2004). Moreover, minocycline has been shown to inhibit VEGF-induced MMP-9 mRNA transcription and protein activation in human aortic VSMCs *in vitro* (Pinney *et al.*, 2003; Yao *et al.*, 2004). More recently, Shahzad *et al.* (2011) showed minocycline to reduce plaque size and vascular stenosis in diet-induced atherosclerosis through a PARP-1 and p27Kip1-dependent mechanism. *In vitro* assays revealed that minocycline reduced the proliferative process in different cell types, including human aortic smooth muscle cells (HASMC) and murine primary aortic VSMCs. These data may explain the lower number of VSMC observed within atherosclerotic plaques of ApoE-/- high-fat diet (HFD) mice treated with minocycline (Shahzad *et al.*, 2011). These authors also established that minocycline's anti-proliferative effect in VSMC depended on p27Kip1, as it induced *in vitro* expression in both VSMCs and HASMCs, and in atherosclerotic plaques analysed *ex vivo*. Of note, the knockdown of p27Kip1 in primary mouse aortic cells abolished the anti-proliferative effect of minocycline. In addition, minocycline reduced poly(ADP-ribose) formation, a marker of PARP-1 activity, in plaques of the truncus brachiocephalicus of ApoE-/- HFD mice and markedly reduced PARP-1 expression, particularly in low-density lipoprotein-treated HASMCs. The reduction of atherosclerotic plaque size after minocycline treatment, mainly due to its anti-proliferative effects on VSMCs, suggests a potential application of minocycline on vascular complications. However, no clinical trials have been conducted yet.

Effects of minocycline on inflammatory bowel disease

The effects of minocycline on experimental colitis were first described in 2009 by Huang *et al.* (2009b), who reported its ability to prevent and treat dextran sodium sulphate-induced colitis, significantly diminishing the mortality rate and attenuating the severity of the disease. These beneficial effects were associated with reduced iNOS and MMP expression in the intestinal tissue. Supporting these observations, Garrido-Mesa *et al.* (2011a) confirmed the intestinal anti-inflammatory effect of minocycline in experimental models of colitis in both mice and rats, showing it to have a higher efficacy than other antibiotics like metronidazole, traditionally used to treat human inflammatory bowel disease, although it was devoid of immunomodulatory properties (Perencevich and Burakoff, 2006). That study proposed that minocycline's ability to modulate both the immune and the microbiological parameters of the disease contribute to its beneficial effects. Regarding the latter, these studies revealed that the imbalance in the composition of the intestinal microbiota that characterizes experimental colitis was restored after minocycline treatment, while the other antibiotics tested did not show this effect. Furthermore, in a mouse model of reactivated colitis, the association of minocycline with the probiotic *Escherichia coli* Nissle 1917, which has been reported to show beneficial effects in these intestinal conditions (Schultz, 2008), exerted a greater intestinal anti-inflammatory effect than the individual treatments and, in addition, was able to attenuate the reactivation of the colitis (Garrido-Mesa *et al.*, 2011b). Therefore, combined immunomodulatory and anti-microbial properties of minocycline could be very useful in the treatment of multifactorial conditions, like inflammatory bowel disease.

Effects of minocycline on allergic asthma

Recently, Joks *et al.* (2010) demonstrated that minocycline can suppress ongoing human and murine IgE responses, without affecting those of IgM, IgG and IgA. In addition, they also reported that minocycline strongly suppressed the *in vitro* induction of the memory IgE antibody-forming responses of spleen and mesenteric lymph node cells from BPO-KLH sensitized mice. The suppression was dose-dependent and IgE isotype-specific (Joks *et al.*, 2010). More recently, it has been described that minocycline suppressed *in vitro* IgE production by peripheral blood mononuclear cells

(PBMCs) from asthmatic subjects, whereas there was no change in IgE levels in PBMC cultures from non-asthmatic subjects. The presence of both $CD4^+$ and $CD8^+$ T lymphocytes was found to be required for the minocycline-mediated suppression of IgE responses by PBMCs of allergic asthmatic humans. Finally, these minocycline-mediated decreases in IgE responses were associated with the suppression of p38 MAPK in the T lymphocytes of these patients (Joks and Durkin, 2011a,b). These effects may account for the improvement observed in allergic asthmatic patients after minocycline treatment in a randomized, double-blind, placebo-controlled, crossover study (Daoud *et al.*, 2008). In that trial, the patients' asthma symptoms and spirometric outcomes were significantly improved, and their oral steroid requirements reduced, findings that indicate the potential usefulness of minocycline for treating asthma.

Effects of minocycline on HIV infection

Several *in vitro* studies have shown minocycline's ability to inhibit HIV activation, proliferation and viral replication in microglia, macrophages and lymphocytes (Si *et al.*, 2004; Zink *et al.*, 2005; Nikodemova *et al.*, 2007). Similarly, it has also been shown to reduce virus infection and immune responses in several experimental models (Si *et al.*, 2004; Zink *et al.*, 2005; Follstaedt *et al.*, 2008; Ratai *et al.*, 2010; Szeto *et al.*, 2010). One of the first studies describing this potential use of minocycline in HIV infection was performed in a simian immunodeficiency virus (SIV) macaque model of HIV-associated neurological damage (Zink *et al.*, 2005). Minocycline-treated SIV-infected macaques were noted to have less severe encephalitis, reduced expression of CNS inflammatory markers and reduced axonal degeneration. In addition, the authors found that treatment with minocycline significantly decreased the viral load in the CSF and plasma and cytotoxic lymphocyte infiltration into the brain. *In vitro* assays revealed that minocycline also decreased p38 activation and HIV replication in primary human lymphocytes, in association with a reduction in MCP-1/CCL2 production (Zink *et al.*, 2005). These findings led to a study focusing on whether minocycline might improve performance in cognitively impaired HIV-infected subjects by the Acquired Immunodeficiency Syndrome (AIDS) Clinical Trials Group (http://clinicaltrials.gov/ct2/show/NCT00361257). In this setting, Szeto *et al.* (2010) demonstrated minocycline to have significant anti-HIV effects in primary human $CD4^+$ T-cells. Antibiotic treatment reduced single-cycle replication, reactivation from a primary $CD4^+$ T-cell-derived model of HIV latency and viral RNA expression after *de novo* infection with the reference strain HIV NL4-3. These *ex vivo* experiments described, for the first time, the ability of minocycline to decrease virus expression from the resting $CD4^+$ reservoirs of HIV-infected patients during highly active anti-retroviral treatment (HAART) and that the anti-HIV effects of minocycline applied to both laboratory and clinical strains of HIV (Zink *et al.*, 2005). Minocycline has been shown to have many effects on $CD4^+$ T-cells that impair HIV by reducing its permissiveness and reactivation from latency. It has been shown to alter T-cell activation, blunting changes in the expression of activation/proliferation markers and cytokine secretion, which are critical for the activation pathways that regulate HIV replication. However, minocycline has also been shown to affect HIV replication, as it dose-dependently decreased the level of productive virus by inhibiting DNA integration or transcription. All these data support the proposition that minocycline would be effective as a novel maintenance therapy in combination with HAART (Szeto *et al.*, 2010).

In addition to the effects of minocycline on $CD4^+$ T-cells and viral replication, the decreased monocyte/macrophage activation caused by this antibiotic can also play a neuroprotective role in SIV-AIDS. Ratai *et al.* (2010) reported, in a non-human primate model of accelerated neuro-AIDS, that none of the minocycline-treated animals developed SIV encephalitis. More recently, Campbell *et al.* (2011) also concluded that, not only its effects on T-cells, but also its inhibitory effect on monocyte activation, correlate with neuronal protection in SIV neuro-AIDS. The authors observed that the reduction of viral replication in $CD14^+$ monocytes *in vitro* after minocycline treatment was directly related to impaired traffic of these cells into the brain. Therefore, there was a correlation between the expansion of activated monocytes and neuronal protection with minocycline. This may result in decreased replication or abundance of $CD14^+CD16^+$ target cells for HIV and SIV *in vivo*, as shown in a rapid model of SIV-neuropathogenesis in rhesus macaques. In this model, minocycline treatment resulted in neuronal protection: it reduced the activation of monocytes and their accumulation in the lymph nodes of treated animals, and inhibited the expression of several markers critical for monocyte traffic and function (CCR2, CD163, CD11b and CD64). These results indicate that the anti-viral effects of minocycline are linked to its ability to reduce the activation of monocytes and their permissiveness to viral infection.

Unfortunately, despite the evidence mentioned earlier, a small pilot study reported that minocycline failed to modulate CSF HIV infection or immune activation in chronic untreated HIV-1 infection (Ho *et al.*, 2011). The chronic infection of the patients enrolled in the study could have presented a level of immune activation and viral replication that minocycline was too weak to modify, as it showed little effect on CNS or systemic macrophage activation and CSF infection. In addition, the absence of encephalitis meant that there might have been little CNS disease to target. Differences in the species (human compared with macaques) and in the disease targets (the duration of the disease and the presence of encephalitis) should be considered. Furthermore, the authors acknowledged limitations in the design of their study (e.g. its small size, short duration and the absence of an untreated control group) that could have led to a type II error and a reduced power to detect effects of minocycline. Nevertheless, the usefulness of minocycline's neuroprotective properties in the treatment of HIV-infection associated cognitive impairment was also ruled out by a clinical trial recently conducted by Sacktor *et al.* (2011). Considering these outcomes and the limitations of the aforementioned trials, larger studies are needed to fully test the effectiveness of minocycline on these measures in AIDS patients. Moreover, given the effects of minocycline reported *in vitro* and in experimental models (Zink *et al.*, 2005; Szeto *et al.*, 2010), there may still be a basis for further study, for example, in well-treated patients in which the level of immunoactivation

is partially attenuated or in combination with anti-retroviral drugs.

Effects of minocycline on autism

FXS is the most common genetic determinant of cognitive impairment and autism spectrum disorders (Koukoui and Chaudhuri, 2007; Penagarikano *et al.*, 2007). Minocycline has been revealed recently as a new possible FXS drug treatment, based on the evidence from various studies involving either experimental animals or humans. In a mouse model of FXS, minocycline promoted the maturation of hippocampal dendritic spines to normal morphology and repressed anxiety and memory defects, effects that may be related to the specific inhibition of MMP-9 (Bilousova *et al.*, 2009). In addition, Siller and Broadie (2011) showed, in a *Drosophila* model of FXS, that neural circuit architecture defects were alleviated by minocycline treatment, which effectively restored the normal synaptic structure. Their results support minocycline as a promising potential FXS treatment and confirmed that it might act via MMP inhibition, as previously reported (Bilousova *et al.*, 2009). In fact, minocycline has been effective in FXS patients, as reported in an open-label add-on trial on FXS patients, which revealed that a wide variety of symptoms were improved by minocycline treatment, including irritability, stereotypy, hyperactivity and inappropriate speech subscales (Paribello *et al.*, 2010; Utari *et al.*, 2010).

Effects of minocycline on osteoporosis

Minocycline benefits bone physiology in several ways. In ovariectomized aged rats, a model for post-menopausal osteoporosis, minocycline was able to both increase bone formation and decrease bone loss in trabecular bone, with a similar efficacy as that observed with oestrogen therapy (Williams *et al.*, 1996). In a subsequent study, minocycline treatment prevented the decrease in bone mineral density induced after ovariectomy and abolished the detrimental effects induced in the femoral trabecular bone area (Williams *et al.*, 1998). In that study, minocycline showed dual effects, modestly reducing bone resorption while substantially stimulating bone formation. In addition, minocycline was found to stimulate the colony-forming efficiency of marrow stromal cells derived from ovariectomized rats, possibly explaining its stimulatory effect on bone formation. Of note, in a rat model of synchronized osseous remodelling, minocycline significantly impaired the disorganization of both the osteoid seam and the layer of osteoblasts, preserved the synthetic activity of osteoblasts and inhibited interstitial collagenase activity and thus bone resorption (Klapisz-Wolikow and Saffar, 1996). Finally, the natural osteotropism that characterize tetracyclines increases their effectiveness in inhibiting MMPs produced by osteoclasts or bone tumour cells (Saikali and Singh, 2003).

Effects of minocycline on cancer

Degradation of the extracellular matrix by MMPs is a critical phenomenon in cancer invasion and metastasis (Hua *et al.*, 2011). Considering the potent inhibitory effects of tetracyclines against MMPs, their anti-cancer potential has been studied in a variety of cancers, including melanoma, lung, breast and prostate cancers (Lokeshwar, 2011). Minocycline has been shown to inhibit *in vitro* invasion and experimental pulmonary metastasis in mouse renal adenocarcinoma (MRAC-PM2) cells (Masumori *et al.*, 1994). In addition, the i.p. administration of minocycline reduced the number of metastatic nodules in the lung when MRAC-PM2 cells were i.v. injected to mice. Minocycline also suppressed the type IV collagenolytic activity of these cells, which can contribute to the suppression of their metastatic potential (Masumori *et al.*, 1994). Considering its osteotropism, minocycline was highly effective in inhibiting MMPs produced by tumour cells in the bone (Saikali and Singh, 2003). Moreover, when combined with celecoxib, minocycline inhibited the osseous metastasis of breast cancer in nude mice, by increasing tumour cell death and decreasing tumour expression of MMP-9 and VEGF (Niu *et al.*, 2008). In addition, minocycline has recently been shown to be a promising new candidate for adjuvant therapy against malignant gliomas, as it reduced glioma growth both *in vitro* and in an experimental mouse model, an effect that was associated with a strongly attenuated expression of membrane type 1 MMP (MT1-MMP) in glioma-associated microglia (Markovic *et al.*, 2011). Furthermore, minocycline has been described to inhibit tumour growth in the xenograft tumour model of C6 glioma cells. This effect was associated with an induction of autophagic cell death, although minocycline still induced cell death through the activation of caspase-3 when autophagy was inhibited (Liu *et al.*, 2011). Therefore, these experimental data confirm that the anti-proliferative, anti-angiogenic and matrix-stimulatory activities displayed by minocycline increase its anti-metastasic and anti-tumour potential. Moreover, minocycline may benefit patients undergoing standard cancer chemotherapy by alleviating drug-induced gut damage. In a model of 5-fluorouracil-induced small intestinal mucositis, minocycline protected mice from gut injury. Body weight loss, diarrhoea and villi measurements were improved by minocycline treatment, which also repressed the expression of TNFα, IL-1β and iNOS, decreased the apoptotic index, and inhibited PARP-1 activity in the mouse small intestine. In addition, minocycline treatment appeared to enhance the anti-tumour effects of 5-fluorouracil in tumour CT-26 xenograft mice (Huang *et al.*, 2009a).

Conclusions

In summary, minocycline has long been used as an antibiotic for acne vulgaris, perioral disease and cutaneous sarcoidosis, and it is currently used for the treatment of inflammatory diseases such as rheumatoid arthritis. However, minocycline has now been demonstrated to have anti-inflammatory, immunomodulatory and neuroprotective effects. Various studies in animal models and some clinical trials have confirmed the beneficial effects and safety of minocycline, alone or combined with other drugs, as a promising therapeutic for diseases with an inflammatory background. Multiple mechanisms of action have been proposed for minocycline, which stands out as a drug affecting multiple targets. Its antioxidant

properties, calcium chelation and ability to inhibit pro-inflammatory enzymes such as iNOS or MMPs may have prominent roles in its beneficial effects in most of the diseases considered in this review. However, other tetracyclines, especially doxycycline, have been reported to share some of these properties, yet have not exhibited a similar efficacy in the same models. Therefore, it seems that it is minocycline's multiple targets that makes it such an outstanding drug among the tetracyclines. In addition, minocycline has been shown to display several attractive advantages that deserve our attention: it is generally considered a safe drug in humans, with a known side-effect profile; it is relatively inexpensive, which makes it suitable for long-term use in these diseases; and, lastly, it is established as an oral therapy, being well absorbed (95–100%) and reaching most of the compartments of the body, including the CNS. Although a better understanding of the mechanisms involved in the action of minocycline *in vivo* is required before its therapeutic potential can be accurately assessed, the encouraging results and attractive merits of this antibiotic indicate that it will have potential as a therapeutic approach for treating many of the diseases described in this review.

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Conflicts of interest

The authors declare no conflicts of interest.

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