Neuroimmunity dynamics and the development of therapeutic strategies for amyotrophic lateral sclerosis
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Amyotrophic lateral sclerosis (ALS) is a fatal paralytic disorder characterized by the progressive and selective loss of both upper and lower motor neurons. In ALS patients, reactive microglia are observed in the motor cortex, motor nuclei of the brainstem, the entire corticospinal tract, the spinal cord, and within the cerebrospinal fluid (Engelhardt and Appel, 1990; Kawamata et al., 1992; Banati et al., 1995). Given the relationship between astrocytes and microglia and the importance of astrocytosis in ALS (Devalos et al., 2009; Yamanaka et al., 2008), it has been hypothesized that microgliosis may also participate in ALS pathogenesis.

In rodent ALS models, microgliosis occurs in pre-symptomatic and symptomatic SOD1G93A mice (Hall et al., 1998; Alexianu et al., 2001; Petrik et al., 2007; Gerber et al., 2012) and at both onset and early-stage of the disease in SOD1H46R mice (Boillee et al., 2007). In ALS patients, reactive microglia are observed in pre-symptomatic and symptomatic SOD1G93A mice that display an activated M2 phenotype and enhance motoneuron survival while microglia isolated from either adult or end stage mice have a classically activated M1 phenotype and induce motoneuron death (Weydt et al., 2004; Liao et al., 2012). In the pre-symptomatic and symptomatic SOD1G93A rat model, microglia aggregates are detected in both the spinal cord and brainstem and display a degenerative and apoptotic phenotype at end stage (Fendrick et al., 2007; Graber et al., 2010). Moreover, microglia of pre-symptomatic SOD1G93A rats express the proliferating marker Ki67 and the phagocytic markers ED1 and major histocompatibility complex (MHC) class II (Sanagi et al., 2010; Bataveljic et al., 2011). These data suggest that microgliosis not only typifies ALS pathogenesis but is also a crucial event in ALS pathogenesis.
but that microglia function changes during disease progression, thus exerting differential effects on motoneurons.

A ROLE FOR MICROGLIA IN ALS PATHOGENESIS

A key finding supporting the contribution of microglia in ALS pathogenesis is the significant extension in lifespan and delay in disease progression when the mutant protein is specifically deleted from microphages and microglial lineages in both SOD1G93A and SOD1G37R mice (Bouiller et al., 2006; Wang et al., 2009). Similarly, bone marrow transplantation (resulting in donor-derived microglia) of SOD1G93A microglia into PU.1−/− mice (that lack CNS microglia at birth) did not induce neurodegeneration whereas wild-type donor-derived microglia transplantation into SOD1G93A, PU.1−/− mice improved survival (Beers et al., 2006).

However, phenotypical analysis of microglia in different regions of SOD1G93A spinal cord suggests that both neuroprotective and neurotoxic population of microglial cells may co-exist during the disease and that depletion of proliferative microglia does not prevent motoneuron degeneration (Cowen et al., 2008; Beers et al., 2011b). Together, these studies thus suggest that microglia participates, through a complex balance between neuroprotective and neurotoxic signals, to ALS disease progression.

PROPOSED MECHANISMS OF MICROGLIAL-DERIVED NEUROTOXICITY

Various misregulated pathways within ALS microglia have been identified that may influence motoneuron survival. Endoplasmic reticulum (ER) stress is a characteristic of ALS pathogenesis (reviewed in Lautenschlaeger et al., 2012). In microglia of both sporadic ALS patients and symptomatic SOD1G93A mice, there is an increased expression of C/EBP homologous protein (CHOP). Ito et al., 2009, a member of the apoptotic ER stress pathway (reviewed in Oyadomari and Mori, 2004). It remains unclear if it directly participates in microglial neurotoxicity but exposure of microglia to interferon gamma (IFNγ), which levels are increased in the spinal cord of ALS mice and patients (Arbiscer et al., 2011; Arbiscer et al., 2012), elicits inducible nitric oxide (NO) synthase (iNOS) expression. The subsequent production of NO can cause an ER stress response that involves CHOP (Kawahara et al., 2001). Interestingly, several SOD1 mouse models show initiation of a specific ER stress response accompanied by microglial activation (Satena et al., 2009).

Activation of the ligand-dependent CD14 lipopolysaccharide (LPS) receptor located at the microglial surface (Lucore et al., 1998) initiates a pro-inflammatory Toll-like receptors (TLR) dependent cascade (Laflamme and Rivest, 2001; Laflamme et al., 1998). Importantly, neurotoxic microglia activation by extracellular stimuli. The release of extracellular nucleotide di- and tri-phosphates, in particular ATP, by degenerating neurons can elicit microglia activation through the ionotropic P2X and metabotropic P2Y purinergic receptors which can subsequently elicit a pro-inflammatory response, chemotaxis, and phagocytosis (reviewed in Inoue, 2006; Bours et al., 2011). Notably, P2X is increased within spinal cord microglia of ALS patients (Yangou et al., 2006). Embryonic microglia and neonatal primary microglial cultures from mutant SOD1 mice display an upregulation of P2Xr, P2Yr, and P2Yr receptors (DYAmbrusio et al., 2009). Further, activation of P2Yr in SOD1G93A microglia leads to the production of significantly higher levels of TNFα, which has a neurotoxic effect on motoneuron cultures (Ugolini et al., 2003), and of cyclooxygenase-2 (Cox-2), which produces the potent inflammatory mediators prostaglandins (D’Ambrosi et al., 2009).

Moreover, a reduced ATP hydrolysis activity in mutant SOD1 microglia, suggests a potentiation of a purinergic-mediated inflammation that can participate to the neuroinflammatory state of microglial cells. Since ATP induces an astrocytic neurotoxic phenotype through P2Yr receptor signaling (Gandtman et al., 2010), one can hypothesize that increased extracellular ATP in ALS, whether exacerbated by motoneurons and/or microglia contributes to the pathogenic microgliosis.

THE POTENTIAL INFLUENCE OF MICROGLIA ON NEURONAL EXCITABILITY

There is presently few assessment of the influence of microglia on motoneuron electrophysiology. However, studies on peripheral nerve or spinal cord injuries show that microglia activation has prominent effects on neuronal inhibitory control and loss of inhibitory control is a contributing mechanism to the motoneuron hyperexcitability that typifies ALS pathogenesis in humans (Bae et al., 2013).

Loss of neuronal inhibitory control occurs by several means including decrease in gamma-aminobutyric acid (GABAergic) interneurons combined with changes in the expression of the GABARa receptor messenger RNA subunit (Perti et al., 2003; Markawa et al., 2004). GABAr and glycine receptors are chloride (Cl−) channels and the expression of cation-chloride cotransporter contributes to inhibitory effects of these Cl− currents (Blaise et al., 2009). Indeed, the entry of Cl− following the opening of GABAr and glycine receptor-gated Cl− channels inhibits neuron excitability by hyperpolarizing membrane potential. Under physiological condition, low intracellular Cl− concentration (Cl−) is maintained by the potassium (K+)–chloride co-transporter KCC2 that extrudes Cl− from mature neurons (Rivera et al., 1999). Stimulation of spinal microglia following peripheral nerve injury induces a decrease in KCC2 expression among dorsal horn nociceptive neurons (Coulil et al., 2003). KCC2 decrease is induced by the brain-derived neurotrophic factor (BDNF) and this is consistent with the previous observation that BDNF can be produced by non-neuronal cells involved in immune responses, including T and B lymphocytes, monocytes, and microglia (Krennstein et al., 1999; Coulil et al., 2005). BDNF produces a depolarizing shift in the anion reversal potential of dorsal horn lamina I neurons due to an increase in (Cl−). This shift prompts an inversion of inhibitory GABA currents that...
contributes to neuropathic pain following nerve injury (Coulil et al., 2005). Decrease in KC2 expression is thus responsible for the excitatory effects of GABA on neurons. Microglia activation and BDNF secretion are mediated through ATP activation of microglial P2X receptors. As discussed earlier, P2X receptors might be involved in ALS pathology since a higher density of P2X-immunoreactive microglial cells/macrophages are found in affected regions of spinal cords from ALS patients (Yangou et al., 2006). Furthermore, levels of BDNF have been found to be increased in microglial cells isolated from ALS mice at the onset of disease and KC2 is decreased in vulnerable motoneurons in SOD1G93A mice (Fuchs et al., 2010; Liao et al., 2012). Additionally, BDNF might play a role in the influence of microglia on motoneuron electric activity as suggested by work on spasticity. Spasticity is characterized by a velocity-dependent increase in muscle tone resulting from hyperexcitable stretch reflexes, spasms and hyper-sensitivity to normally innocuous sensory stimulations. Spasticity develops following spinal cord injury and is also regarded as an ALS clinical symptom (Rowland and Shneider, 2001). The main mechanism hypothesized to be responsible for spasticity is increased motoneuron excitability and increased synaptic inputs in response to muscle stretch due to reduced inhibitory mechanisms. Recently, it has been demonstrated that, following spinal cord injury, increased levels of BDNF mediated spasticity, due to post-transcriptional downregulation of KC2 (Bojenguz et al., 2010). Together, these studies suggest that reactive microglia in ALS may exert an aberrant effect on the electrical activity of motoneurons and highlight the importance of furthering our understanding of this functional interaction.

Lastly, a hypothetical scenario relates to the defect in astrocytic glutamate transporter and the neurotoxic accumulation of the excitatory amino acid. It has been demonstrated that TNFα promotes glutamate release by activated microglia through the cystine/glutamate exchanger (Xc; Piani and Fontana, 1994). Though the implication of the Xc system in ALS has not yet been investigated, it may represent a potential mechanism of microglia-mediated excitotoxicity that warrants further study (Qin et al., 2006).

**THE DUAL ROLE OF NEUROIMMUNITY IN MOTOONEURON DISEASE**

**PATHOLOGICAL PHENOTYPE OF THE IMMUNE SYSTEM IN ALS**

In addition to astrocytes and microglia, blood-derived immune cells may also play synergistic and critical functions during disease progression. Presence of a systemic immune activation is suggested by abnormalities observed in the blood and the CSF of ALS patients such as increased numbers of circulating lymphocytes (CD4+ helper T cells, CD8+ cytotoxic T lymphocytes, CTL, and natural killer, NK cells), increased expression of MHC class II molecules on monocytes as well as higher levels of inflammatory chemokines and cytokines (regulated on activation normal T cell expressed and secreted, RANTES, monocyte chemotactic protein, MCP-1, IL-12, IL-15, IL-17, and IL-23; Zhang et al., 2005; Rentzos et al., 2007, 2010, 2012; McCombe and Henderson, 2011). Further, post-mortem studies of brain and spinal cord lesions from ALS patients show that the activation and proliferation of microglia is associated with an infiltration of activated macrophages, mast cells and T lymphocytes which are found in close proximity to degenerating tissues (Engelhardt et al., 1993; Graeser et al., 2004; Lewis et al., 2012). An in-depth autopsy of six ALS patients reveals an enrichment of T-cell receptor Vβ2-positive T cells in the spinal cord and CSF, suggesting an antigen-driven T cell selection (Panzera et al., 1999). Finally, ALS patients with a more rapidly progressing pathology show decreased numbers of regulatory T lymphocytes (Tregs), suggesting that the number of Tregs is inversely correlated with disease progression (Beers et al., 2011a; Rentzos et al., 2012). Tregs secrete anti-inflammatory cytokines such as IL-4, IL-10 and transforming growth factor beta (TGF-β) and have been shown to induce the production of the neurotrophic factors glial-derived neurotrophic factor (GDNF) and BDNF by astrocytes (Reynolds et al., 2007). Tregs are also able to dampen a T helper (Th1) pro-inflammatory response and attenuate toxic microglial responses. Contribution of the innate immune system is also suggested by the presence of immunoglobulins and complement deposition as well as a significant increase of NK cells in the blood of ALS patients (Donnenfeld et al., 1984; Engelhardt and Appel, 1990; Rentzos et al., 2012). While these investigations of ALS samples and tissues do not assess the contributory role of the immune system to disease pathogenesis, they do highlight its active presence.

In support of what is observed in humans, ALS rodent models also display a particular immunological phenotype. Indeed, SOD1G93A mice have allowed the demonstration that the inflammatory cellular subtypes are phenotypically and functionally different depending upon the disease stage (Liao et al., 2012). During the initial stages, infiltrating CD4+ T cells are mainly Th2 (IL-4+) while there is a skew toward Th1 (IFNγ+) cells and CD8+ T cells (both IL-17A positive and negative) as the disease progresses (Fiala et al., 2010; Beers et al., 2011b). Alteration in inflammatory cell subtypes is associated with, and maybe driven by, differences in Tregs. Interestingly, early symptomatic SOD1G93A mice have an increased number of Treg and a decreased proliferation of effectors T lymphocytes (Teffs), whereas a decreased numbers of Tregs and an increased proliferation of Teffs is found in end stage animals (Beers et al., 2011a; Zhao et al., 2012). The innate immune system is also affected in ALS rodents, displayed by the substantial increase of NKT cells firstly in the liver and then in the spinal cord of SOD1G93A mice (Chiu et al., 2008; Finkelstein et al., 2011).

Whether neuroinflammation is a cause or a consequence of motoneuron dysfunction is still debated. It is interesting to note that inflammation is not limited to the CNS but systemic with a correlation between disease expression and levels of plasma LPS as well as the numbers of activated circulating monocytes and T lymphocytes (Zhang et al., 2005, 2009). A thymic dysfunction also parallels the neurodegenerative process in mutant SOD1 mice and ALS patients (Sekenyen et al., 2010). In the CNS of ALS patients, TAR DNA-binding protein 43 (TDP-43) displays an increased expression and interacts with nuclear factor kappa B (NF-kB) in glial and neuronal cells. LPS-activation of NF-kB in microglial cells expressing the TDP-43 mutant is associated with the production of pro-inflammatory cytokines, including TNFα, IL-1β, IL-6, and IFNγ (Swarup et al., 2011). NF-kB, is also an important intermediate of the TLR signaling pathway that contribute to the initiation of inflammatory responses (O’Connell et al., 2012). The
Alzheimer’s disease was also shown to lead to the down regulation of acetylcholine receptors (Rosas-Ballina et al., 2011). Regarding ALS pathogenesis, an inflammatory response taking part of the autonomic homeostatic cells has been described to produce acetylcholine to modulate the mRNA is a target of TDP-43 (Polymenidou et al., 2011), and the accumulation of mRNA in the spinal cord of SOD1 mutant mice, early in the disease phase, a dysfunction of the cholinergic circuit has been reported and that these functions vary during disease progression. There is increasing evidence that inflammatory cells mediate interesting target for the development of novel treatments. How might play a key role in ALS pathogenesis and may represent an inherited mutation in the gene coding for TDP-43. TDP-43 binds to RNA in the nucleus, including the regulation of alternative pre-mRNA splicing, mRNA export, and stability as well as the processing of misfolded RNA (Garcia and Caceres, 2007). Interestingly, TDP-43 can directly interact with Drosha, Dicer and Dicer (Kawahara and Mieda-Sato, 2012). The activity of Dicer, which processes miRNA precursors at the RNA-induced silencing complex (Wilson and Doudna, 2013), is required to maintain motoneuron functional integrity. Indeed, the conditional deletion of Dicer in mice with motor neurons expressing the pathogenic human SOD1G93A produces a deletion of axonal cell bodies leading to motoneuron degeneration and denervation atrophy in mice (Hazama et al., 2011). Another intriguing link with the miRNA pathway in the neuro-immune interaction has been recently revealed by the demonstration that the neurotransmitter acetylcholine can inhibit the production of pro-inflammatory cytokines, TNFα and IL-6, through induction of miRNA-124 in macrophages (Sun et al., 2013). In addition, a subset of CD4+ T cells has been described to produce acetylcholine to mediate the inflammatory response towards the autonomic nervous system. acetylcholine can inhibit the production of pro-inflammatory cytokines, such as TNFα, IL-1β, and IL-6. Therefore, CD4+ T cells may play a role in the regulation of the inflammatory response in the spinal cord. The key role of this balance between protective and deleterious immune responses in modulating clinical outcome is confirmed by the temporal and regional association between neuroinflammatory response and clinical outcome is confirmed by the temporal and regional association between neuroinflammatory response and motor neuron degeneration but is actively involved in the neurodegenerative process. Tregs and Th2 lymphocytes assume the majority of the neuroprotective functions of the immune system and targeting these neuroprotective Tregs are increased in the peripheral blood of ALS patients during early stages but their numbers decrease as the disease progression accelerates and are thus inversely correlated with disease progression rates (Beers et al., 2011a; Rentzos et al., 2012; Henkel et al., 2013). Furthermore, Foxp3 and CD25 expression is reduced in Tregs from rapidly progressing patients and are also inversely correlated with disease progression rates (Henkel et al., 2013). Co-culture experiments showed that Tregs suppress the expression of cytokines from virus-infected cells, or tumorigenic cells (Zhang and Bevan, 2011; Rentzos et al., 2012). The passive transfer of Tregs into ALS mice lacking functional T cells results in lengthened disease duration and prolonged survival (Beers et al., 2011a). Interestingly, at symptomatic stage, an increased number of CD8+ T and NK cells is observed in the blood and spinal cord of ALS patients (Calvo et al., 2010; Rentzos et al., 2012). Neurotrophic effects might be associated with a Th1-driven CTL pro-inflammatory immune response. Accordingly, mutant SOD1 T cell lymphocytes proliferate to a greater extend and produce more neurotrophic factors than controls. The information from pre-clinical models and ALS patients suggests that systemic immune activation (innate and adaptive) might play a key role in ALS pathogenesis and may represent an interesting target for the development of novel treatments. However, a better understanding of the specific roles played by the different subtypes of immune cells is of utmost necessity. Indeed, accumulating evidence suggests that inflammatory cells mediate both protective and deleterious effects on motoneuron survival and that these functions vary during disease progression.

### The Protective Function of the Immune Response in ALS

Protective immunity, a crucial homeostatic phenomenon in the repair of damaged tissues, results from both the clearance of debris and the effects of cytokines and growth factors delivered by inflammatory cells to the site of injury. (Hohlfeld et al., 2000; Schwartz and Moolen, 2001). The neuroprotective ability of immune cells is also evident in ALS. Indeed, when SOD1G93A mice are bred with mice lacking functional T cells or CD4+ T cells, microglia skew toward an M1 inflammatory phenotype and disease progression accelerates, suggesting that CD4+ T cells provide neuroprotection by suppressing the activation of cytotoxic microglia. Accordingly, reconstitution of T cells following bone marrow transplantation of SOD1G93A mice lacking functional T cells prolonged their survival and suppressed the activation of M1 microglia (Beers et al., 2008). Further analysis showed that neuroprotection is mainly supported by CD4+ CD25+ Foxp3+ Tregs that secrete IL-4, thus promoting M2 protective microglia and IL-4 secreting Th2 cells, while inhibiting the neurotoxic Th1 response and IFNγ secretion. The passive transfer of Tregs into ALS mice lacking functional T cells results in lengthened disease duration and prolonged survival (Beers et al., 2011a). Accordingly, these neuroprotective Tregs are increased in the peripheral blood of ALS patients during early stages but their numbers decrease as the disease progression accelerates and are thus inversely correlated with disease progression rates (Henkel et al., 2013). Co-culture experiments showed that Tregs suppress the expression of cytokines from virus-infected cells, or tumorigenic cells (Zhang and Bevan, 2011; Rentzos et al., 2012). The passive transfer of Tregs into ALS mice lacking functional T cells results in lengthened disease duration and prolonged survival (Beers et al., 2011a). Therefore, the inflammatory infiltrate observed in ALS is also evident in ALS. Indeed, when SOD1G93A mice are bred with mice lacking functional T cells or CD4+ T cells, microglia skew toward an M1 inflammatory phenotype and disease progression accelerates, suggesting that CD4+ T cells provide neuroprotection by suppressing the activation of cytotoxic microglia. Accordingly, reconstitution of T cells following bone marrow transplantation of SOD1G93A mice lacking functional T cells prolonged their survival and suppressed the activation of M1 microglia (Beers et al., 2008). Further analysis showed that neuroprotection is mainly supported by CD4+ CD25+ Foxp3+ Tregs that secrete IL-4, thus promoting M2 protective microglia and IL-4 secreting Th2 cells, while inhibiting the neurotoxic Th1 response and IFNγ secretion. The passive transfer of Tregs into ALS mice lacking functional T cells results in lengthened disease duration and prolonged survival (Beers et al., 2011a). Accordingly, these neuroprotective Tregs are increased in the peripheral blood of ALS patients during early stages but their numbers decrease as the disease progression accelerates and are thus inversely correlated with disease progression rates (Henkel et al., 2013). Co-culture experiments showed that Tregs suppress the expression of cytokines from virus-infected cells, or tumorigenic cells (Zhang and Bevan, 2011; Rentzos et al., 2012). The passive transfer of Tregs into ALS mice lacking functional T cells results in lengthened disease duration and prolonged survival (Beers et al., 2011a). Therefore, the inflammatory infiltrate observed in ALS lesions appears not simply as a consequence of motoneuron degeneration but is actively involved in the neurodegenerative process. Tregs and Th2 lymphocytes assume the majority of the neuroprotective functions of the immune system and targeting their signaling pathways may be an attractive therapeutic strategy in ALS.

### The Neurotoxic Function of the Immune Response in ALS

Cytotoxic T lymphocytes and NK cells are important effector cells of the immune system that eliminate aberrant cells, classically virus-infected cells, or tumorigenic cells (Zhang and Bevan, 2011; Kaur et al., 2012). Interestingly, at symptomatic stage, an increased number of CD8+ T and NK cells is observed in the blood and spinal cord of ALS patients (Calvo et al., 2010; Rentzos et al., 2012). Neurotrophic effects might be associated with a Th1-driven CTL pro-inflammatory immune response. Accordingly, mutant SOD1 T cell lymphocytes proliferate to a greater extend and produce more...
A and B isoforms are increased in the serum of ALS patients such as IL-17 or IL-22 (Cella et al., 2010). NK cells thus represent a response via the combined action of other NK-related cytokines. Further, the production of IFN-γ by activated NK cells of granzyme serine proteases that subsequently induce caspase activation and cell death (van Domselaar and Boven, 2008). Interestingly, the activation of Fas triggers a death pathway in motoneurons that appeared restricted to this cell type (Raoul et al., 1999, 2002, 2006; Bernard-Marissal et al., 2012; Adischer et al., 2013). Motoneurons expressing ALS-linked SOD1 mutations showed an increased susceptibility to Fas-mediated death through activation of a Fas/NO amplification loop (Raoul et al., 2002, 2006). Accordingly, mutant SOD1 mice with homozgyous loss-of-function Fas mutation present a reduced loss of motoneurons and a prolonged life expectancy (Petti et al., 2005). It remains to be determined whether CTL contribute to Fas-induced motoneuron loss. Another cytotoxic mechanism of CTL-mediated killing of target cells is the perforin-granzyme system. Upon recognition of a target cell by CTL, cytotoxic granules containing perforin and granzyme are released in the extracellular space. Perforin is a pore forming protein allowing the entry in the target cells of granzyme serine proteases that subsequently induce caspase activation and cell death (van Domselaar and Boven, 2011). It is noteworthy that increased levels of granzyme A and B isoforms are increased in the serum of ALS patients (Ilieca, 2011). However, the functional significance of such an increase remains to be determined. IFN-γ, which is produced by CTL cells, can exert both immunostimulatory and immunomodulatory effects during an immune response. IFN-γ produced by mutant astrocytes and motoneurons can elicit a death program in motoneurons through the activation of the lymphotxin beta receptor (LT-βR) by its ligand LIGHT (Adischer et al., 2011, 2012). The genetic deletion of LIGHT in SOD1G93A mice suggests that the LIGHT pathway contributes to the progression phase of the disease. Recently, the intracellular activation of granzyme is increased in ALS patients, which induce specific motoneuron alterations both in vitro and in vivo after passive transfer in mice (Appel et al., 1994; Gourie-Devi et al., 1997). Similarly, drugs used to target specific neuroinflammatory effectors that showed promising
results in pre-clinical models such as celecoxib and pioglitazone (Drachman et al., 2002; Schutz et al., 2005), proved to be ineffective in improving motor functions and survival in ALS patients (Cudkowicz et al., 2006; Dupuis et al., 2012).

The progressive spreading, extension and diffusion of the neurodegenerative process that typically occurs in ALS patients may result from the concurrent progressive invasion of the CNS by glial cells and most importantly, the functional changes that take place within these cells. Importantly, an incomplete understanding of said changes could lead to undesired and unexpected results. Indeed, both minocycline and thalidomide (an analog of lenalidomide) revealed serious harmful effects in patients during a randomized placebo-controlled phase III trial and a single arm, open label phase II study, respectively (Gordon et al., 2007; Stommel et al., 2009).

As translational therapy targeting neuroinflammatory and immunomodulatory effectors is rapidly progressing, it has become clear that a step backward is presently required to better assess the temporal functional changes that occur within glial and immune cells in ALS pathogenesis. The cellular environment being composed of both neuroprotective and neurotoxic functions, specific therapeutic windows may dictate the choice of drugs and their pathogenic targets. Alternatively, a combinatory therapeutic approach may be more efficient at modulating the contributions of non-neuronal cells to ALS pathology. Thus, while neuroinflammation undoubtedly plays a role in ALS pathogenesis, therapeutic
success will be reached in limiting the activation and amplification of toxic glial and immune cells whilst preserving the cellular subtypes that are beneficial to motoneuron survival.

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