Lipoic acid reduces inflammation in a mouse focal cortical experimental autoimmune encephalomyelitis model

Priya Chaudhary [a,*], Gail Marracci [a,b], Danielle Galipeau [a], Edvinas Pocius [a], Brooke Morris [a], Dennis Bourdette [a,b,c]

[a] Department of Neurology, Oregon Health & Science University, L226, 3181 SW Sam Jackson Park Road, Portland, OR 97239, United States
[b] Research, Department of Veteran Affairs Medical Center, 3710 SW U.S. Veterans Hospital Road, Portland, OR 97239, United States
[c] Neurology Services, Department of Veteran Affairs Medical Center, Portland, OR 97239, United States

ARTICLE INFO

ABSTRACT

Cortical lesions are a crucial part of MS pathology and it is critical to determine that new MS therapies have the ability to alter cortical inflammatory lesions given the differences between white and gray matter lesions. We tested lipoic acid (LA) in a mouse focal cortical EAE model. Brain sections were stained with antibodies against CD4, CD11b and galectin-3. Compared with vehicle, treatment with LA significantly decreased CD4+ and galectin-3+ immune cells in the brain. LA treated mice had fewer galectin-3+ cells with no projections indicating decrease in the number of infiltrating monocytes. LA significantly reduces inflammation in a focal cortical model of MS.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

Multiple sclerosis (MS) is a debilitating disease that causes inflammation, demyelination, neuronal injury and axonal loss in the central nervous system. MS has traditionally been thought to be a disease associated with white matter, but recent studies have shown substantial cerebral cortex lesions and gray matter pathology (Vercellino et al., 2005). The histopathological characteristics of gray matter lesions differ from the lesions located in the white matter. Experimental autoimmune encephalomyelitis (EAE) is an important animal model that has been successfully used to study and develop various therapies for MS. There have been many different ways of inducing MS like disease in mice but none of the existing mice models are suitable to understand the heterogeneity of cortical lesions in the brain. Focal lesion models can be used to monitor specific lesions and treatment effects. Various focal EAE models have been developed in rats by injecting cytokines (Kerschensteiner et al., 2004; Merkler et al., 2006) and vascular endothelial growth factor (Sasaki et al., 2010) in spinal cord or brain.

Airas et al., 2015 used stereotactic injection of heat-killed Bacillus Calmette–Guerin (BCG) and activation using intradermal injection of BCG in complete Freund adjuvant. In this paper we assessed a focal cortical lesion model in mouse by injecting proinflammatory cytokines in mice immunized with myelin oligodendrocyte glycoprotein (MOG). We used this focal model to study the effects of lipoic acid on brain cortical lesion.

Lipoic acid is a natural antioxidant. It suppresses and treats EAE and EAON (Chaudhary et al., 2011; Chaudhary et al., 2006; Marracci et al., 2002; Morini et al., 2004; Schreibelt et al., 2006). LA mediates its effect by inhibiting T cell migration into the CNS, decreasing endothelial cell adhesion molecule expression and reduction in MMP-9 production. The objective of this study was to determine the effects of LA on inflammatory cells in a focal cortical EAE model of MS.

2. Material and methods

2.1. EAE induction and disease scores

EAE was induced in C57BL/6 (The Jackson Laboratory, Bar Harbor, ME) female mice (8–10 weeks old). C57BL/6 were immunized with 200 μg of MOG 35–55 peptide (PolyPeptide Laboratories, San Diego, CA) in complete Freund's adjuvant containing 400 μg of *Mycobacterium tuberculosis* per mouse by subcutaneous (s.c.) injection (a total volume of 0.2 ml). Pertussis toxin (List Biological Labs Inc., Campbell, CA) was

---

administered by intraperitoneal (i.p.) injection at day 0 (75 ng per mouse) and day 2 (200 ng per mouse) after immunization. Mice were scored daily for EAE by using a 9-point scale as described in Forte et al., 2007.

2.2. Intracerebral stereotactic injections

Unimmunized and MOG immunized mice were anesthetized by isoflurane and mounted on a stereotactic device. A hole was drilled through the skull using co-ordinates Bregma +1 mm, lateral 1 mm and depth 1.05 mm (©2014 Allen Institute for Brain Science. Allen Mouse Brain Atlas). Mice received intracerebral (i.c.) stereotactic injections containing cytokines or PBS. The injection of 2 μl of cytokine solution containing tumor necrosis factor -α (TNF-α; 250 ng; Sigma, St. Louis, MO) and 10,000 U of interferon-γ (IFN-γ, Sigma, St. Louis, MO) dissolved in phosphate-buffered saline (PBS) was injected slowly throughout a 5-minute period using an ultra micro- injector pump (WPI, Sarasota, FL). For control experiments mice were injected with 2 μl of PBS without cytokines. Initial experiments were performed using unimmunized mice and the mice were sacrificed 3, 5 and 7 days post injection (Fig. 1a). Maximum galectin-3 positive cells were found 3 days post injection therefore all further experiments in unimmunized and MOG immunized mice were done at three days after cytokine injection. Unimmunized mice were sacrificed 3 days after i.c. injection (Fig. 1b). In mice immunized with MOG intra-cerebral injections were given 12 days post-immunization (Fig. 1c). Mice (unimmunized and MOG immunized) were divided into 4 groups, namely, vehicle-PBS (received vehicle s.c. and PBS i.c. injection), LA-PBS (received LA s.c. and PBS i.c. injection), vehicle-cytokine (received vehicle s.c. and cytokine i.c. injection) and LA-cytokine (received LA s.c. and cytokine i.c. injection).

Intra-cerebral injections were made on one side of the brain because in some animals the inflammatory cells spread to the non-injected contralateral side of the brain. In all cases the post-surgical recovery was without incident.

2.3. Lipoic acid administration in mice

LA was prepared as described in Chaudhary et al. (2011). Briefly, LA (50 mg, Sigma, MO) was weighed and re-suspended in 0.35 ml 2 N NaOH. Sterile water (4.5 ml) was added and titrated with approximately 0.05 ml 10 N HCl or until LA barely precipitated. pH was adjusted to 7.2–7.4. The solution was filter sterilized through a 0.2 μm low protein binding syringe filter and frozen in aliquots until used. 0.4 ml LA (5 mg/ml) was administered by s.c. injection (100 mg/kg). Equal volume of a normal saline solution was used as a vehicle-control. In unimmunized mice LA or vehicle was administered 5 days before i.c. injection (Fig. 1b). MOG immunized mice received either daily s.c. injections of LA (100 mg/kg) or vehicle beginning on day 7 after immunization. Mice were sacrificed 15 days after immunization (Fig. 1c).

2.4. Quantitative immunohistochemical studies

For quantitative immunofluorescent analyses, brain sections (30 μm) around the site of injection were collected serially and used for antibody staining. The sections were permeabilized, washed, blocked (0.5% fish skin gelatin/3% BSA) in PBS, and then incubated with primary antibody at 4 °C overnight. After incubation in secondary antibody, sections were mounted in Prolong Gold antifade and imaged using laser scanning confocal microscope system (Carl Zeiss, LSM 780, Thornwood, NY).

Primary antibodies that recognized CD4 (BD PharMingen, San Diego, CA; 1:25 dilution) and Mac-1 (CD11b; Leinco Technologies, St. Louis, MO; 1:75 dilution) were used to identify T cells and microglia/macrophage populations, respectively. Activated microglia/macrophages (R&D Systems, Minneapolis, MN; 1:50 dilution) were detected using galectin-3. Anti CD45 (BD Biosciences, San Jose, CA; 1:200 dilution) was used to distinguish between macrophages and microglia. Axonal damage was assessed by SMI312 (Covance, San Diego, CA; 1:500 dilution) and MBP (Novus Biologicals, Littleton, CO; 1:100 dilution) staining was used to evaluate demyelination. All secondary antibodies were
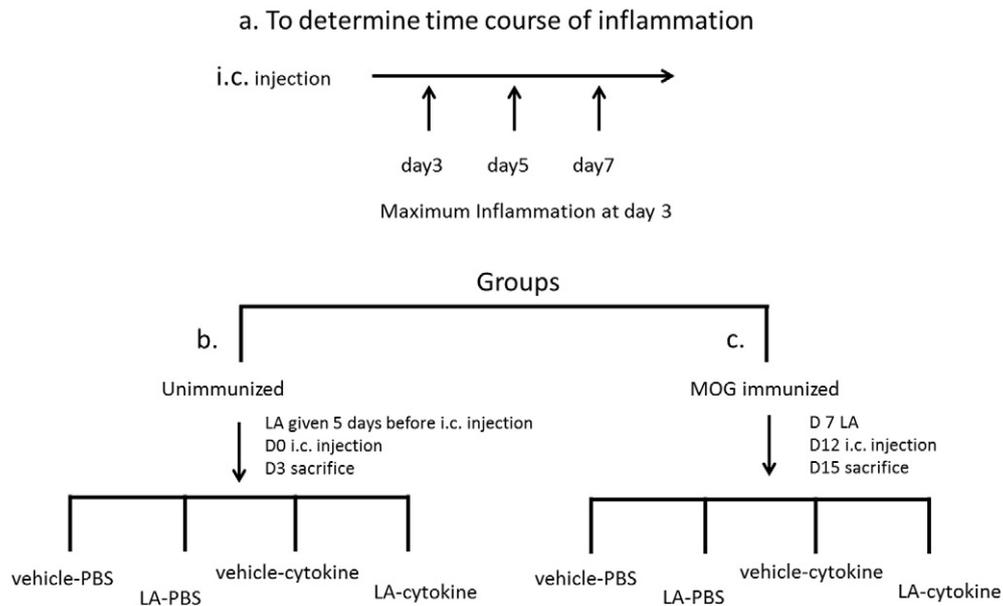
Fig. 1. Schematic illustration of the experimental design. a. Cytokines were stereotactically injected and mice were sacrificed at different times following injection. Once peak of inflammation was determined to be 3 days post cytokine injection mice were divided into two groups b. Unimmunized and c. MOG immunized. Both groups were further subdivided into 4 groups vehicle–PBS (received vehicle s.c. and PBS i.c. injection), LA–PBS (received LA s.c. and PBS i.c. injection), vehicle–cytokine (received vehicle s.c. and cytokine i.c. injection) and LA–cytokine (received LA s.c. and cytokine i.c. injection).
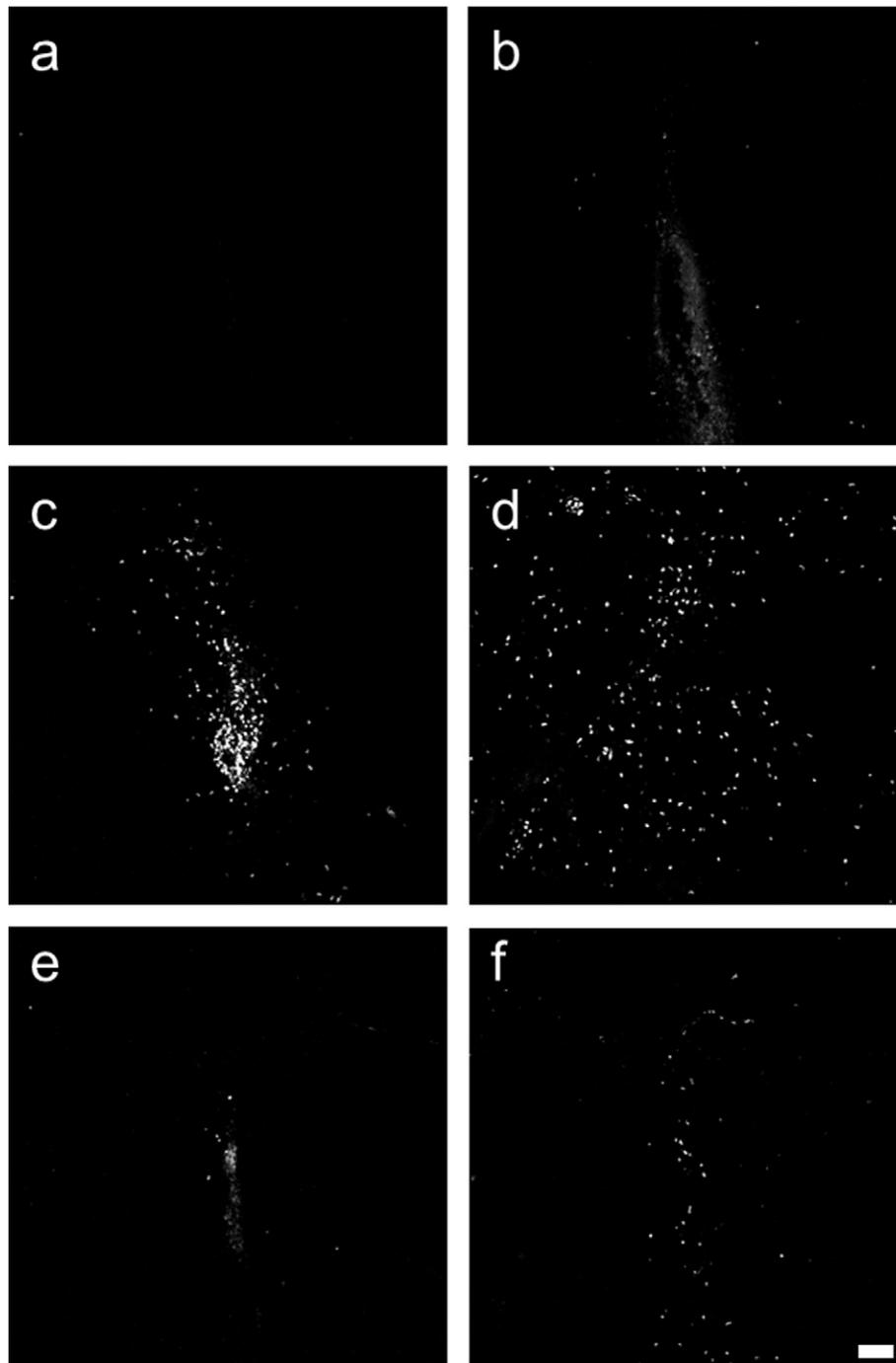
Fig. 2. CD4 positive cells around site of injection. a, b Unimmunized mice, c–f MOG immunized mice. a, c. Vehicle–PBS; b, d vehicle–cytokine; e. LA–PBS; f. LA–cytokine. Scale bar 100 μm. Notice that unimmunized mice have very few CD4 cells (a, b) as compared with MOG immunized mice (c, d). LA–PBS and LA–cytokine groups from unimmunized mice are not shown in the figure as they did not have many CD4 cells.

from Invitrogen, Carlsbad, CA (1:200 dilution). Alexa Fluor 488 donkey anti-rat IgG (A21208), Alexa Fluor 488 goat anti-mouse IgG (A11029), Alexa Fluor 555 goat anti-rabbit IgG (A21428) and Alexa 546 donkey anti goat IgG (A11056) were used as the secondary antibodies. To quantify immunofluorescence, sections were imaged (10×, 20× or 40× objectives) on a Zeiss confocal microscope. Negative controls

were generated by omitting the primary antibody. An additional control comprised omission of both primary and secondary antibodies.

Immunofluorescence data were analyzed 200 μm away from the injection site using quantitative methods. Data analysis was done using MetaMorph software, v7.6.3; Molecular Devices, CA. Total area corresponding to 0.25 mm^2 was analyzed left and right side of injection

Fig. 3. Inflammation at the site of injection in unimmunized mice (a–f) and MOG immunized mice (g–r). These sections demonstrate the high density of inflammatory cells at the site of injection. There is increased number of galectin-3 positive cells when cytokines are injected. The inflammatory cells spread beyond 200 μm from the site of injection (e). Density of galectin-3 positive cells when cytokines are injected is higher in MOG immunized animals (k) as compared to unimmunized animals (e). LA decreases the galectin-3 positive cells (q). a–c, g–i vehicle–PBS; d–f, j–l vehicle–cytokine; m–o LA–PBS; p–r LA–cytokine. CD11b is green; galectin-3 is red. Scale bar 200 μm.
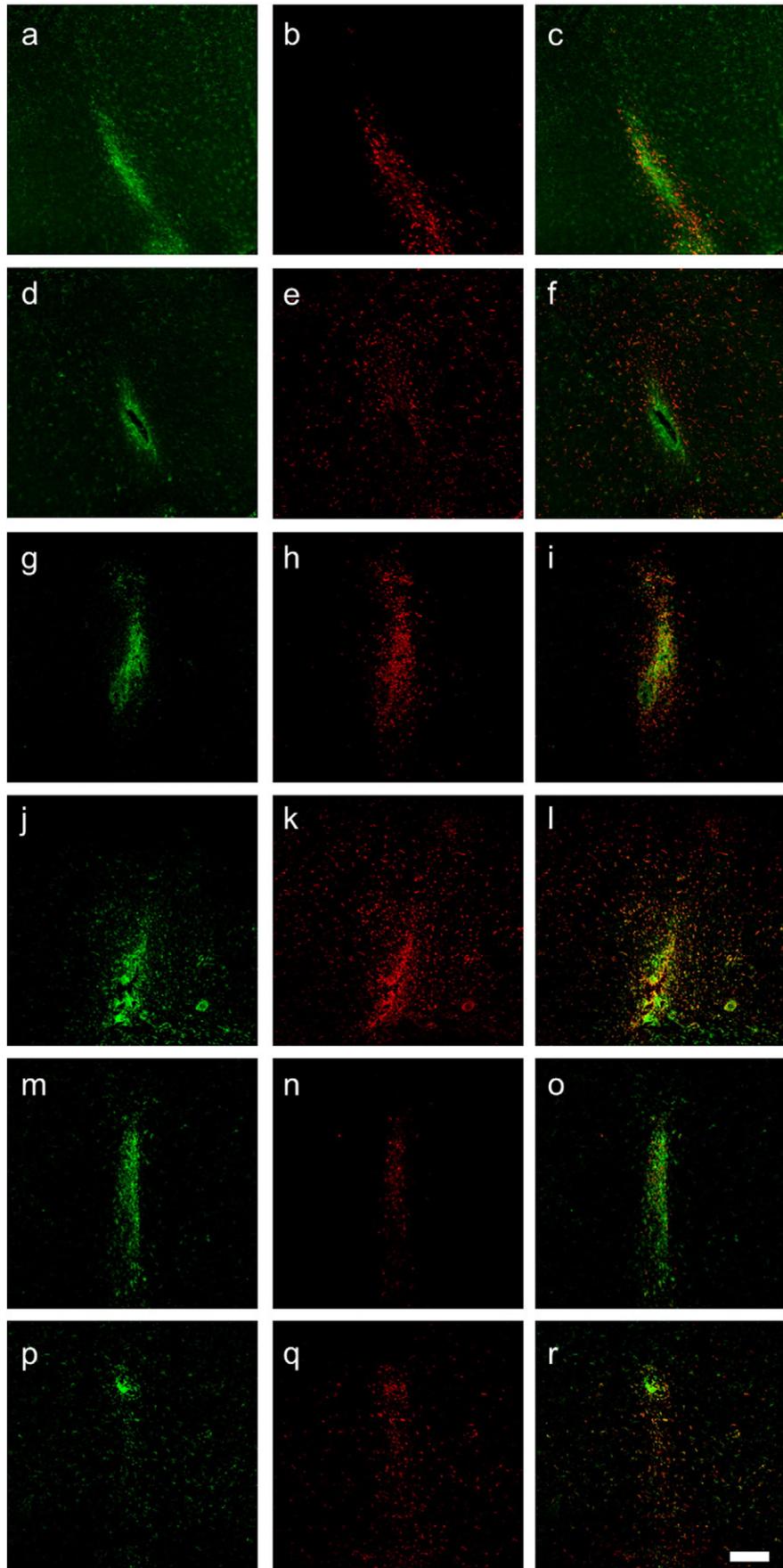
Table 1

shows the percent area stained with antibody in coronal brain sections from mice not immunized with MOG, n = 3 mice each group. These mice were injected with cytokines or PBS in the brain and did not develop the disease symptoms. Measurements were made 200 μm away from site of injection.

	Vehicle–PBS	LA–PBS	Vehicle–cytokine	LA–cytokine
CD4	0.04 ± 0.006	0.06 ± 0.01	0.05 ± 0.01	0.05 ± 0.01
CD11b	1.78 ± 0.18	1.94 ± 0.24	1.05 ± 0.14	0.99 ± 0.12
Galectin-3	0.02 ± 0.01	0.01 ± 0.01	1.21 ± 0.13	1.53 ± 0.22

site. Thresholding and intensity measurement methods of image analysis were used. Image analyses were done blinded to treatment. The average background fluorescence was determined. Similar methods have been used for quantification of CD4+ and CD11b+ cells in spinal cords of mice with EAE (Chaudhary et al., 2006; Forte et al., 2007; Chaudhary et al., 2011).

2.5. Statistical analyses

Statistical analyses were performed using the Mann–Whitney U-test. Statistical significance was defined as $p < 0.05$ for all analyses.

3. Results

3.1. Injection of proinflammatory cytokines in the brain—non-immunized mice

The formation of EAE lesions in a predetermined location was achieved by stereotactic injections of the proinflammatory cytokines, TNF-α and IFN-γ, in the cerebral cortex of B6 mice. Brain sections that contained the site of injection were analyzed after staining with antibodies against T cells, macrophages and monocytes. The site of injection was marked by heavy infiltration of inflammatory cells as evident in Figs. 2, 3. Inflammation was detected by staining with anti CD4, CD11b and galectin-3.We measured the inflammation spread about 200 μm from the site of injection. In initial experiments mice were injected with either PBS or TNF-α/IFN-γ (cytokine) and sacrificed at day 3, 5 and 7 after stereotactic injection. CD4 positive T cells were detected in the group that received cytokines (0.19% staining at day 3, 0.08% at day 5, 0.03% at day 7, n = 2). Cytokine injection led to influx of galectin-3 positive cells into the brain but not in mice that received PBS. The galectin-3 positive cells peaked at day 3 (2.70% staining at day 3, 1.7% at day 5, 1.11% at day 7, n = 2). We next repeated the PBS and cytokine stereotactic injection in mice but further divided them into those that received vehicle or LA subcutaneously. The results are presented in Table 1, Fig. 2a,b, Fig. 3a–f, also see supplementary Fig. 1. There were hardly any CD4 cells and no galectin-3 positive cells 200 μm away from the site of injection in the group that got i.c. injections of PBS (received vehicle or LA s.c.) indicating galectin-3 to be a specific marker for spread of inflammatory cells (Table 1) after injection of cytokines. There was no significant difference in inflammatory cells in the groups that received vehicle–cytokine and LA–cytokine (Table 1).

3.2. Injection of proinflammatory cytokines in the brain—mice immunized with MOG

Based on the findings from the cytokine injections in non-immunized mice we studied mice immunized with MOG. Immunized mice were stereotactically injected with cytokine or PBS at onset of disease at day 12 and sacrificed 3 days later (Table 2). Mice immunized with MOG when injected with cytokine mixture led to a formation of a large lesion with inflammatory cells (CD4, CD11b and galectin-3 positive cells) in the cortex. The number of inflammatory cells in MOG immunized mice was much greater than in unimmunized mice that received cytokine stereotactic injection (compare Fig. 2b vs d, Fig.

Table 2

compares EAE scores from the 4 different groups. Average scores from 10 mice are represented in the table. Mice that received LA did not get sick.

Day	Vehicle–PBS	LA–PBS	Vehicle–cytokine	LA–cytokine
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0.6	0	0.2	0
13	1.0	0	0.1	0
14	1.5	0	0.6	0
15	2.7	0	1.5	0

3d–f vs j–l, supplementary Fig. 1). In our model there is a lack of axonal and myelin injury aside from injury at injection site which occurs in mice injected with PBS and cytokines (Supplementary Fig. 2).

3.3. LA inhibits infiltration of inflammatory cells into brain lesion in mice immunized with MOG

Our previous studies have shown that LA suppresses inflammation in EAE and EAON therefore we focused on early time point (day 3 after i.c. injection) to see whether LA can inhibit inflammation in the brain with compromised blood brain barrier. As reported before, LA suppressed paralysis resulting from spinal cord lesions in EAE (Table 2). Mice that received LA did not develop disease. The clinical scores do not reflect the inflammation in the brain as the inflammatory response is mostly a result of cytokine injection. Brain sections from mice that received vehicle or LA (100 mg/kg) s.c. injections and PBS or cytokine i.c. injection were analyzed. Table 3 demonstrates that LA significantly reduced CD4 positive T cells and galectin-3 positive activated microglia/macrophages after i.c. cytokine injection. The % area occupied by CD4+ T cells was 1.02 ± 0.23 in mice receiving vehicle–cytokine and 0.13 ± 0.01 in mice receiving LA–cytokine (p < 0.0001). The % area with galectin-3 + microglia/macrophages was 5.99 ± 0.49 in mice that received vehicle–cytokine and 3.31 ± 0.29 in mice that received LA–cytokine (p < 0.0001) (Table 3, compare Fig. 2d vs f; Fig. 3j–l vs p–r). Staining with CD11b did not significantly reduce in mice that received LA and i.c. cytokine injection. No significant differences in inflammatory cells were detected in vehicle–PBS and LA–PBS (Table 3, compare Fig. 3g–i and m–o).

3.4. LA reduces infiltrating monocytes

Galectin-3 positive cells could be classified into two different morphologies (Fig. 4), one that did not have projections and the other had multiple projections. We measured galectin-3 positive cells with and without projections in the 4 groups (Table 4). Mice that received i.c. PBS injections did not have many galectin-3 + cells. Mice that received i.c. cytokine injection had many galectin-3 positive cells. The mice that received LA had reduced number of cells without projections. We identified these cells as infiltrating monocytes. We further stained the brain slices with anti CD45 (infiltrating monocyte/macrophage marker). LA receiving mice showed faintly labeled and reduced number of CD45 cells as compared to those that received vehicle (Fig. 5).

Table 3

shows the percent area stained with antibody in coronal brain sections from mice immunized with MOG, n = 10 mice each group. Measurements were made 200 μm away from site of injection. *Mann Whitney test vehicle-cytokine vs LA-cytokine p < 0.0001.

	Vehicle–PBS	LA–PBS	Vehicle–cytokine	LA–cytokine
CD4	0.11 ± 0.02	0.08 ± 0.02	1.02 ± 0.23	0.13 ± 0.01*
CD11b	2.03 ± 0.17	2.31 ± 0.21	3.12 ± 0.38	2.33 ± 0.18
Galectin-3	0.20 ± 0.04	0.07 ± 0.02	5.99 ± 0.49	3.31 ± 0.29*

Table 4

shows the number of galectin-3 positive cells. *Mann Whitney test vehicle–cytokine vs LA–cytokine p < 0.0001.

	Cells with projections	Cells without projections	Total cells	Mice number
Vehicle–PBS	2	24	26	4
LA–PBS	9	5	14	4
Vehicle–cytokine	137	807	944	10
LA–cytokine	178	393*	571	10

4. Discussion

We assessed changes in inflammatory cells and provide critical information on the cortical lesion dynamics. This article provides new insights about LA being effective in reducing inflammation in cortical focal EAE model. LA reduced CD4 + T cells and galectin-3 + activated microglia/macrophages in brain lesion in mice immunized with MOG and stereotactically injected with cytokines. We further demonstrate that LA reduces CD45 positive cells thus showing that infiltrating monocytes are reduced.

The model presented in this paper is similar to focal EAE model in Lewis rats that has been developed previously in spinal cord (Kerschensteiner et al., 2004) and brain (Merkler et al., 2006) by stereotactic injections of cytokines. Cytokines like TNF-α and IFN-γ are involved in the progression of neurologic disorders (Benveniste and Benos, 1995) and have been used widely to study inflammation (Gardner et al., 2013; Simmons and Willenborg, 1990; Sun et al., 2004). Not many CD4 positive cells were detected in cytokine injected unimmunized mice (Table 1; Fig. 2b). Interestingly, cytokine injection in unimmunized mice caused increase in galectin-3 positive cells that was not detected when only PBS was injected in the cortex (Table 1; Fig. 3 compare b, e). Significant increase in cortical inflammation was dependent on peripheral immune priming against MOG peptide as many inflammatory cells were not detected in mice where MOG priming was not done. Cytokine injection caused increase in T cell infiltration and microglial activation (Fig. 2d; Fig. 3j–l, Table 3) in the cerebral hemispheres of MOG immunized mice. All these results indicate differences in the local inflammatory response in normal vs MOG sensitized brains. Studying the lesion 3 days after cytokine injection is similar to the biopsy samples from newly diagnosed MS cases that contain numerous infiltrating immune cells. Cortical lesions can be differentiated into active or chronic lesions on the basis of number of immune cells (Calabrese et al., 2010). The majority of phagocytic cells in cortical lesions are described to have the morphology of activated microglia and only some of these cells have morphology associated with macrophages (Peterson et al., 2001). We used galectin-3/Mac-2, a member of the galectin family of beta-galactoside binding lectins as a marker for activated microglia and macrophages (Reichert and Rotshenker, 1999). Galectin-3 is not expressed in undamaged CNS. Additionally, we demonstrate that LA reduced T cell, activated microglia and macrophages (Fig. 2e–f, Fig. 3m–r). We classified the galectin-3 positive cells into two types based on whether or not they had projections (Fig. 4). Based on the morphology described by Yamasaki et al., 2014 — the type with projections are probably microglia-derived macrophages and the ones that do not have projections are infiltrating monocytes or monocyte-derived macrophages.

Anti CD45 was used to further distinguish between invading macrophages and microglia. CD45 is a membrane bound protein tyrosine phosphatase and is present in cells of monocyte/macrophage lineage. We confirmed the presence of CD45 positive cells in brains which were injected with cytokines and that did not receive LA (Fig. 5). LA treated mice that received cytokine injection had very few lightly stained CD45 positive cells. Thus, we provide evidence that the infiltrating monocytes/macrophages are suppressed by lipoic acid treatment (Table 4 and Figs. 4, 5). This study provides a rationale for investigating the ability of LA to reduce development of inflammatory cortical lesions in MS. Our next steps are to understand the mechanisms of action of LA on microglia and monocytes in long term focal EAE model.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi: http://dx.doi.org/10.1016/j.jneuroim.2015.10.011. These data include the Google map of the most important areas described in this article.
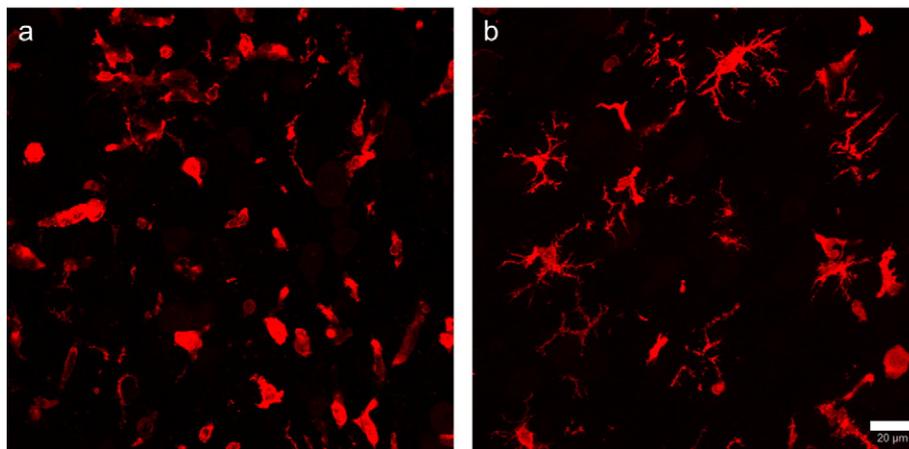
Fig. 4. LA reduces galectin-3 positive cells without projections. a. Vehicle–cytokine. b. LA–cytokine. Scale bar = 20 μm.
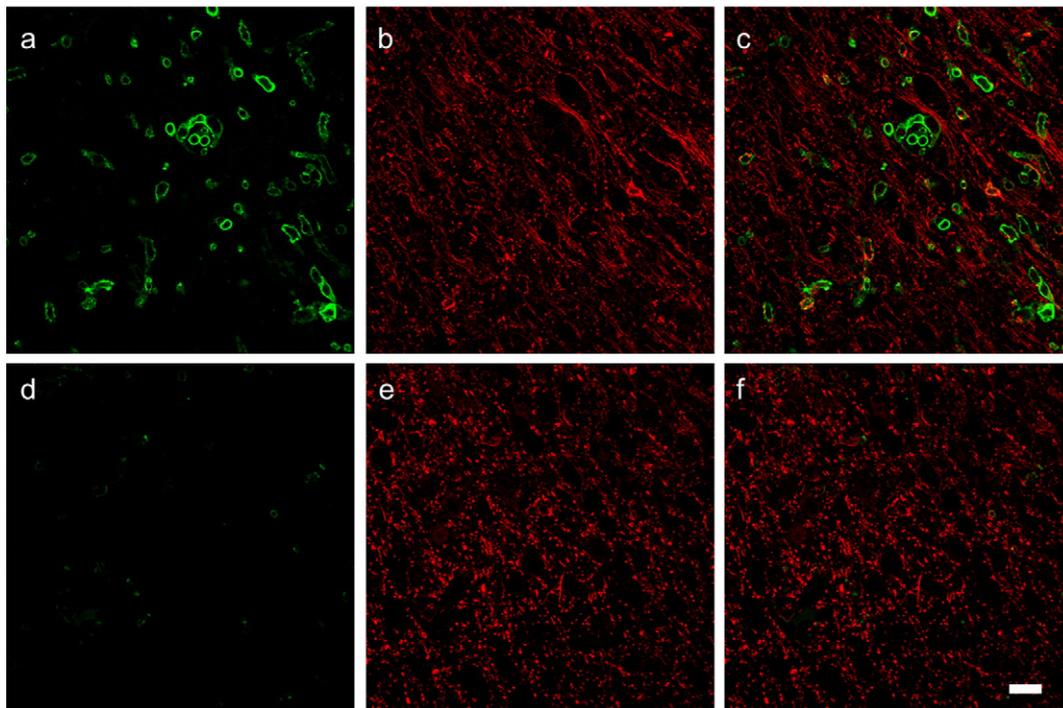
Fig. 5. LA reduces infiltrating macrophages stained with anti CD45. Top panel vehicle–cytokine, bottom LA–cytokine. a, d CD45; b, e MBP; c f overlays. Scale bar = 20 μm.

References

Airas, L., Dickens, A.M., Elo, P., Marjamäki, P., Johansson, J., Eskola, O., Jones, P.A., Trigg, W., Solin, O., Haaparanta-Solin, M., Anthony, D.C., Rinne, J., 2015. In vivo PET imaging demonstrates diminished microglial activation after fingolimod treatment in an animal model of multiple sclerosis. J. Nucl. Med. 56 (2), 305–310.

Benveniste, E.N., Benos, D.J., 1995. TNF-alpha- and IFN-gamma-mediated signal transduction pathways: effects on glial cell gene expression and function. FASEB J. 9 (15), 1577–1584 Review.

Calabrese, M., Filippi, M., Gallo, P., 2010. Cortical lesions in multiple sclerosis. Nat. Rev. Neurol. 6 (8), 438–444.

Chaudhary, P., Marracci, G.H., Bourdette, D.N., 2006. Lipoic acid inhibits expression of ICAM-1 and VCAM-1 by CNS endothelial cells and T cell migration into the spinal cord in experimental autoimmune encephalomyelitis. J. Neuroimmunol. 175, 87–96.

Chaudhary, P., Marracci, G., Yu, X., Galipeau, D., Morris, B., Bourdette, D.N., 2011. Lipoic acid decreases inflammation and confers neuroprotection in experimental autoimmune optic neuritis. J. Neuroimmunol. 233 (1–2), 90–96.

Forte, M., Gold, B.G., Marracci, G., Chaudhary, P., Basso, E., Johnsen, D., Yu, X., Fowlkes, J., Rahder, M., Stem, K., Bernardi, P., Bourdette, D., 2007. Cyclophilin D inactivation protects axons in experimental autoimmune encephalomyelitis, an animal model of multiple sclerosis. Proc. Natl. Acad. Sci. U. S. A. 104, 7558–7563.

Gardner, C., Magliozzi, R., Durrenberger, P.F., Howell, O.W., Rundle, J., Reynolds, R., 2013. Cortical grey matter demyelination can be induced by elevated pro-inflammatory cytokines in the subarachnoid space of MOG-immunized rats. Brain 136 (Pt 12), 3596–3608.

Kerschensteiner, M., Stadelmann, C., Buddeberg, B.S., Merkler, D., Bareyre, F.M., Anthony, D.C., Linington, C., Brück, W., Schwab, M.E., 2004. Targeting experimental autoimmune encephalomyelitis lesions to a predetermined axonal tract system allows for refined behavioral testing in an animal model of multiple sclerosis. Am. J. Pathol. 164 (4), 1455–1469.

Marracci, G.H., Jones, R.E., McKeon, G.P., Bourdette, D.N., 2002. Alpha lipoic acid inhibits T cell migration into the spinal cord and suppresses and treats experimental autoimmune encephalomyelitis. J. Neuroimmunol. 131, 104–114.

Merkler, D., Ernsting, T., Kerschensteiner, M., Brück, W., Stadelmann, C., 2006. A new focal EAE model of cortical demyelination: multiple sclerosis-like lesions with rapid resolution of inflammation and extensive remyelination. Brain 129 (Pt 8), 1972–1983.

Morini, M., Roccatagliata, L., Dell'Eva, R., Pedemonte, E., Furlan, R., Minghelli, S., Giunti, D., Pfeffer, U., Marchese, M., Noonan, D., Mancardi, G., Albini, A., Uccelli, A., 2004. Alpha-lipoic acid is effective in prevention and treatment of experimental autoimmune encephalomyelitis. J. Neuroimmunol. 148, 146–153.

Peterson, J.W., Bo, L., Mork, S., Chang, A., Trapp, B.D., 2001. Transected neurites, apoptotic neurons, and reduced inflammation in cortical multiple sclerosis lesions. Ann. Neurol. 50, 389–400.

Reichert, F., Rotshenker, S., 1999. Galectin-3/MAC-2 in experimental allergic encephalomyelitis. Exp. Neurol. 160 (2), 508–514.

Sasaki, M., Lankford, K.L., Brown, R.J., Ruddle, N.H., Kocsis, J.D., 2010. Focal experimental autoimmune encephalomyelitis in the Lewis rat induced by immunization with myelin oligodendrocyte glycoprotein and intraspinal injection of vascular endothelial growth factor. Glia 58 (13), 1523–1531.

Schreibelt, G., Musters, R.J., Reijerkerk, A., de Groot, L.R., van der Pol, S.M., Hendrikx, E.M., Dopp, E.D., Dijkstra, C.D., Drukarch, B., de Vries, H.E., 2006. Lipoic acid affects cellular migration into the central nervous system and stabilizes blood–brain barrier integrity. J. Immunol. 177, 2630–2637.

Simmons, R.D., Willenborg, D.O., 1990. Direct injection of cytokines into the spinal cord causes autoimmune encephalomyelitis-like inflammation. J. Neurol. Sci. 100 (1–2), 37–42.

Sun, D., Newman, T.A., Perry, V.H., Weller, R.O., 2004. Cytokine-induced enhancement of autoimmune inflammation in the brain and spinal cord: implications for multiple sclerosis. Neuropathol. Appl. Neurobiol. 30 (4), 374–384.

Vercellino, M., Plano, F., Votta, B., Mutani, R., Giordana, M.T., Cavalla, P., 2005. Grey matter pathology in multiple sclerosis. J. Neuropathol. Exp. Neurol. 64 (12), 1101–1107.

Yamasaki, R., Lu, H., Butovsky, O., Ohno, N., Rietsch, A.M., Cialic, R., Wu, P.M., Doykan, C.E., Lin, J., Cotleur, A.C., Kidd, G., Zorlu, M.M., Sun, N., Hu, W., Liu, L., Lee, J.C., Taylor, S.E., Uehlein, L., Dixon, D., Gu, J., Floruta, C.M., Zhu, M., Charo, I.F., Weiner, H.L., Ransohoff, R.M., 2014. Differential roles of microglia and monocytes in the inflamed central nervous system. J. Exp. Med. 211 (8), 1533–1549.