Myelin biogenesis

Ozgen, Hande

Chapter 5

TNFα induces actin cytoskeletal rearrangements in mature oligodendrocytes and reallocates MBP; consequences for (re)myelination

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Abstract

Multiple sclerosis (MS) is a demyelinating disease, characterized by inflammation, demyelination, failure of remyelination, and axonal loss. Pro-inflammatory cytokines are elevated in MS and contribute to MS pathology. Here, we examined the effect of the pro-inflammatory cytokine TNFα on myelin membrane integrity of oligodendrocytes, grown in primary and mixed myelinated cultures. Interestingly, treatment of myelinated spinal cord-derived cultures caused a reduction of the length of the MBP-positive internodal segments. Exposure of mature oligodendrocytes to TNFα did not affect protein and mRNA levels of the structural myelin protein MBP; neither did the cytokine interfere with cell survival and oligodendrocyte differentiation. However, in TNFα-treated oligodendrocytes, MBP protein was localized mainly in the cell body and primary processes, rather than in the myelin sheets. Upon removal of TNFα the preferential localization of MBP was again in the myelin sheets. Remarkably, while the myelin typical galactolipid galactocylceramide redistributed to TX-100-soluble membranes upon TNFα treatment, the altered localization of MBP is not reflected by detergent (in)solubility. However, TNFα treatment perturbed the organization of the actin cytoskeleton, which was accompanied by a redistribution of MBP from actin-dependent to actin-independent membrane microdomains. The ensuing decompaction appears to interfere with the barrier function of MBP, given that treatment with TNFα causes a similar redistribution of other myelin proteins, including PLP and CNP. Hence, our findings revealed that transient exposure to TNFα alters the internodal length of myelin by altering the actin cytoskeleton and the localization of myelin proteins and lipids, thereby likely allowing for myelin remodeling, while persistent exposure to TNFα might eventually interfere with myelin compaction.

1. Introduction

In the central nervous system (CNS) oligodendrocytes (OLGs) form myelin sheaths that are necessary for correct impulse conduction and support of neurons. Damage to OLGs and myelin has deleterious consequences, as reflected by the chronic neurodegenerative disease multiple sclerosis (MS), which is characterized by inflammation, demyelination, failure of remyelination and axonal loss. The pro-inflammatory cytokine TNFα appears to be one of the key players in MS pathology. This is illustrated by elevated TNFα levels in MS lesions [1–3], and in patient-derived T-cells [4,5], and TNFα levels in the cerebrospinal fluid (CSF) correlate with the degree of disability [6,7]. Moreover, in MS patients blood levels of TNFα are upregulated

before and during exacerbations [5,8], while patients with relapsing-remitting MS show a concomitant transient increase of TNFα levels [9]. In anti-cytokine therapy, a diminished production of TNFα reduces the incidence and causes a delay in the onset of EAE [9], without affecting, however, the disease severity once EAE has been established [11]. Unfortunately, clinical trials with monoclonal anti-TNF antibodies were unsuccessful, and even resulted in exacerbated inflammation [12,13], indicating that TNFα has both adverse and beneficiary effects in MS.

Cytokines regulate a wide variety of cellular functions in developing and mature brain. TNFα, for example, is highly expressed in the embryonic brain [14]. However, mouse studies revealed that TNFα signalling is not essential for brain development or behaviour [15,16]. Rather, it is upon CNS injury that cytokines seem to play a more prominent role. Infiltrating cells of the immune system, including lymphocytes and monocytes, but also residential glial cells, produce numerous cytokines in response to a changing environment, such as in demyelinating lesions, and they may shape cellular reactions, in either a (transient) inhibitory or beneficiary manner, that influence repair capacity. TNFα has been claimed to be essential for correct remyelination by inducing proliferation of oligodendrocyte progenitor cells (OPCs), as observed in a toxin-induced demyelination model [17]. However, in other studies it has been shown that TNFα hampers both OPC differentiation to mature myelin producing OLGs and OLG survival [18–22]. For expressing its activity, TNFα can bind to two related receptors, 55-kDa TNFR1 and 75-kDa TNFR2, and is therefore capable of many and opposing cellular responses [23,24]. Cells of the OLG lineage express both TNF receptors; TNFR2 is particularly expressed during early development [25], and contributes to remyelination [17]. By contrast, TNFR1 expression is not developmentally regulated and has been suggested to mediate primarily demyelination [12].

Upon CNS injury, TNFα levels will be upregulated and, in addition to OPCs, also existing ‘healthy’ myelin membranes will become exposed to this cytokine. Therefore, we examined the influence of TNFα on mature OLGs, focussing on the dynamics of myelin basic protein (MBP), a major myelin protein, located at the cytoplasmic surface of the myelin membranes. MBP is a basic, membrane-associated adhesive structural protein, and imperative for myelination [26–28]. Its adhesive properties organize the close apposition and compaction of the inner membrane leaflets, where it may also act as an ‘entry port’ for myelin components [29]. MBP isoforms that lack exon-II are transported to the myelin sheath in their mRNA form [30–32], which is thought to circumvent premature adhesion of membranes [26,28,33], whereas exon-II containing MBP isoforms remain in the cell body, where they localize to the nucleus and cytoplasm [28,34,35]. Here we report that TNFα induces a reorganization of the actin cytoskeleton, along with a lateral redistribution of MBP from actin-dependent to

actin-independent membrane microdomains. In addition we observed a reallocation of MBP towards the cell body and primary processes, which may lead to shortening of existing myelin segments. The in vivo significance of these data may relate to a beneficiary effect of TNFα upon remyelination, allowing existing myelin segments to shorten in order to provide space to newly formed myelin segments and paranodes for 'remodeling'.

2. Materials and Methods

2.1. Cell cultures

Primary oligodendrocytes. Primary OLGs and astrocyte cultures were generated by a shake-off procedure as described previously [36]. Enriched OPCs were resuspended in SATO medium containing 10 ng/mL PDGF-AA (Peprotech, Rocky Hill, NJ) and 10 ng/mL FGF-2 (Peprotech). For immunocytochemical studies, OPCs were plated on poly-L-lysine (PLL, 5 µg/ml, Sigma, St. Louis, MO)-coated 13-mm glass coverslips (VWR, Amsterdam, The Netherlands) in a 24-well plate at 30,000 cells per well (500 µL), and for qPCR and Western blot analysis on PLL-coated 10-cm dishes (Nunc) at 1 × 106 cells per dish (6 mL). After 48 hrs, differentiation was induced by growth factor withdrawal, and cells were cultured in SATO supplemented with 0.5% fetal calf serum (FCS, Bodinco, Alkmaar, The Netherlands). 7 days after initiating differentiation the majority of the OPCs matured towards MBP-positive OLGs bearing myelin-like membranes (myelin sheets). These mature OLGs were exposed to 20 ng/ml recombinant rat TNFα (Peprotech) for 3 days, unless otherwise indicated. For the recovery experiments, the cells were allowed to recover in SATO+0.5% FCS for 24 hrs. For the TNFR1 blocking experiments, cells were treated with the antibody 1 hr prior to TNFα treatment. The TNFR1 blocking antibody (TNFR1, E20, 1:100, Santa Cruz, Huissen, Netherlands, [37]) was present throughout the experiment.

Myelinated spinal cord cultures. Myelinated spinal cord cultures were generated from 15 days old Wistar embryo's (Harlan, the Netherlands), as described before, with minor modification [38]. Briefly, meninges were removed from isolated spinal cords, minced in 1 ml MEM, and subjected to enzymatic digestion by adding 100 µl of 2.5% trypsin solution (Sigma) and 80 µl of liberase (2.5 mg/ml; Roche, Diagnostics, Mannheim, Germany) for 20 minutes at 37°C. To stop digestion, 1 ml of SD solution [0.52 mg/ml trypsin soybean inhibitor (Sigma); 0.04 mg/ml bovine pancrease DNase (Roche); 3 mg/ml BSA) in L-15 medium] was added for 3 minutes. Next, cells were gently triturated and centrifuged at 1000 rpm for 5 minutes. The cell pellet was resuspended in plating medium [PM; 50% DMEM (Gibco, Paisley, UK); 25% horse

serum (Invitrogen); 25% HBSS (Gibco) and 2 mM glutamine], and cells were plated onto 13 mm coverslips with an astrocyte monolayer at a density of 150,000 cells/coverslip (500 µl/well). Notably, the astrocytes were derived from the remaining astrocyte monolayer after shaking off the OPCs. The monolayer was trypsinized and passaged once before cells were plated on PLL-coated (5 µg/ml) 13-mm coverslips (VWR) at a density of 60,000/coverslip in 10% FCS in DMEM (500 µl/well) for 3 days. The dissociated spinal cords were allowed to attach for 2 hrs, after which 500 µl of differentiation medium [(DM) DMEM supplemented with 1 mg/ml holotransferin (Sigma), 20 mM putrescine (Sigma), 4 µM progesterone (Sigma), 6 µM selenium (Sigma), 10 ng/ml biotin (Sigma), 50 nM hydrocortisone (Sigma) and 10 µg/ml insulin (Sigma)] was added. Half of the volume of medium was replaced every second day with fresh DM. After 12 days in vitro (DIV), insulin was omitted. At 19 DIV, cultures were treated with or without 10 ng/ml TNFα.. TNFα was added upon each medium change, i.e., every 2 days. The cultures were analysed at 26 DIV.

2.2. LDH and MTT assay

The LDH and MTT assay were performed as described previously [36]. Briefly, mature OLGs, i.e., 7 days after initiating differentiation, were exposed to the indicated TNFα concentrations for 3 days, after which the medium (LDH assay) and cells (MTT) were analyzed. To determine the cytotoxicity of TNFα, the release of LDH into the medium was measured using a commercial LDH assay kit (Roche, Indianapolis, IN) according to manufacturer's instructions. The effect on cell viability was determined with an MTT assay on the remaining cells. Cytotoxicity (LDH) and cell viability (MTT) are expressed as the percentage of control cells, which was set at 100%.

2.3. Isolation of Triton X-100-resistant membrane microdomains

Cells were subjected to 1% Triton X-100 (TX-100) extraction at 4°C, followed by 10-30-40% discontinuous OptiPrep density gradient centrifugation of equal protein amounts, as previously described [39]. Fractions were collected from top (1) to bottom (7), the membrane microdomains being present at fractions 3 and 4, after which equal volumes of each fraction were subjected to Western blot (60 µl) and dotblot (10 µl) analysis.

2.4. Isolation of detergent free lipid rafts

Detergent-free lipid rafts were isolated as described by Klappe et al. [40]. Primary

cells were scraped in base buffer (20 mM Tris/HCl, pH 7.8, and 250 mM sucrose, 1 mM CaCl2 and 1 mM MgCl2) on ice and centrifuged at 250 g for 2 minutes. The pellet was suspended in 1 ml base buffer supplemented with a cocktail of protease (Complete Mini, Roche) and phosphatase (Calbiochem, Cocktail set II, La Jolla, CA) inhibitors. The suspension was homogenized by passaging 20 times through a 25-gauge needle and centrifuged at 1000 g for 10 minutes. This procedure was repeated, and the first and second post-nuclear supernatant (PNS) were combined. To equal protein amounts of the PNS (in a total volume of 2 ml), 2 ml of base buffer containing 50% OptiPrep (Axis-Shield PoC AS, Dundee, Scotland) was added. On top of this mixture, an 8 ml continuous gradient of 0–20% OptiPrep buffer was poured with the use of a gradient mixer. After centrifugation at 22,000 rpm for 90 min at 4°C (Beckman SW41 rotor), 9 fractions of 1.34 ml were collected (from top to bottom) and half of this fraction volume was subjected to TCA precipitation [41] followed by Western blot and dotblot analysis.

2.5. Western Blot and dotblot analysis

Cells were scraped in PBS, and lysed on ice for 30 min in TNE-lysis buffer (50 mM Tris-HCl, pH 7,5, 150 mM NaCl, 5 mM EDTA, 1% TX-100 and protease and phosphatase cocktail inhibitors). For Western blot analysis, equal protein (lysates) or volume amounts (gradients) were mixed with SDS reducing sample buffer, heated for 5 min at 95 °C and subjected to SDS-PAGE. Samples were loaded onto 15% SDS-polyacrylamide gels and subjected to Western blot analysis as described previously [36]. Primary antibodies used were polyclonal rat anti-MBP (1:2000, Millipore) and monoclonal mouse anti-β-actin (1:2000, Sigma). For dotblot analysis, equal volumes of the gradient fractions (10 µl) were applied onto nitrocellulose membrane, and when dried subjected to similar immunoblot analysis as described above for the Western blots. Primary antibodies were anti-GalC antibody O1 (ammonium sulfatide precipitated, 1:3000) and anti-sulfatide O4 antibody (ammonium sulfatide precipitated, 1:400), which were both a kind gift of Dr. Guus Wolswijk [42]. The signals were detected using appropriate IRDye®-conjugated secondary antibodies (Li-Cor Biosciences, Lincoln, NE) and the Odyssey Infrared Imaging System (Li-Cor Biosciences). The protein bands were quantified by imaging software Image J.

2.6. qPCR analysis

Total RNA from cells was isolated using the InviTrap Spin Cell RNA Mini Kit (Stratec molecular, Berlin, Germany). Total RNA (1 µg) was reversed transcribed in the

presence of oligo(dT)12-18 and dNTPs (Gibco) with superscript II reverse transcriptase (Roche) according to the manufacturer's instructions. qPCR amplifications were performed on copy DNA using primers specific for rat MBP with exon-II (forward, 5'-CACATGTACAAGGACTCACAC-3'; reverse 5'-GAAGAAGTGGACTACTGGGT-3'), rat MBP without exon-II (forward, 5'- ACTTGGCCACAGCAAGTACC-3'; reverse, 5'-TGTGTGAGTCCTTGCCAGAG-3') and the house-keeping genes HBMS (forward, 5'-CCGAGCCAAGCACCAGGAT-3; reverse, 5'-CTCCTTCCAGGTGCCTCAGA-3'), and HPRT1 (forward, 5'- GACTTGCTCGAGATGTCA-3'; reverse, 5'- ACCACCCTGTTGCTGTAG-3'). The results were analyzed with StepOne software and normalized to the house-keeping genes HBMS and HPRT1.

2.7. Immunocytochemical analysis

Monocultures. Cells were gently fixed with 2% paraformaldehyde (PFA) for 15 min at room temperature (RT), followed by incubation with 4% PFA for 15 min. Fixed cells were blocked and permeabilized, respectively with 4% bovine serum albumin (BSA) and 0.1% TX-100 for 30 min. The cells were incubated for 60 min at RT with polyclonal rat anti-MBP (1:100, Millipore, Temecula, CA), monoclonal anti-CNP (1:100, Sigma), monoclonal anti-PLP (4C2, 1:10, kind gift of Dr. Vijay Kuchroo (Harvard Medical School, Boston,[43]), or monoclonal anti-mouse β-tubulin (1:500, Sigma) antibodies. After three times washing with phosphate buffered saline (PBS), cells were incubated with appropriate TRITC- or FITC-conjugated secondary antibodies (1:50, Jackson ImmunoResearch Laboratories, Inc., West Grove, PA) diluted in 4% BSA in PBS for 30 min at RT, followed by three times PBS washing. During secondary antibody incubation, DRAQ5 (1:500, Bistatus Limited, Leicestershire, UK) and TRITC-conjugated phalloidin (1:200, Sigma) were also included to visualize the nuclei and F-actin, respectively. For double staining, cells were sequentially stained with the different antibodies. Cells were mounted in DAKO mounting medium. Images were acquired by a confocal laser scanning microscope (Leica SP8 AOBS CLSM, Leica Microsystems, Heidelberg, Germany), equipped with an argon laser (488 nm), 2 He/Ne lasers (552 and 633 nm, respectively) and Leica Confocal Software. A 63×/1.25 oil immersion objective was used for 3-channel scanning (488 nm, 552 nm, 633 nm). Images of single cells were acquired with similar gain settings and 15 cells were measured at each condition. To quantify the cellular distribution of protein or mRNA, i.e., cell body and primary processes and myelin sheets, the cells were segmented in 'in' (encompassing the cell body and primary processes) and 'out' (constituting the remaining processes and sheets) by selection by hand and in a blinded manner. Since OLGs grown in vitro do not form a continuous sheet covering the supporting glass coverslip, the

area within the selections that did not hold cellular material was eliminated by a treshhold to only visualize cellular material. The cellular distribution was defined as the ratio between fluorescent intensity between 'out' and 'in', i.e., a value above 1 corresponded to a relative enrichment in the myelin membrane.

Myelinated-cultures. Cultures were fixed in 4% PFA and incubated at RT in 0.5% TX-100 in 5% normal goat serum (NGS, Vector Laboratories, Burlingame, CA) for 60 min. After washing with PBS, cells were incubated for 2 hrs at RT with monoclonal rat anti-MBP (1:250, Serotec, Oxford, UK), and anti-NF-H antibodies (1:5000, EnCor Biotechnology Inc, Gainesville, FL) diluted in 2% NGS. Staining was visualized by an incubation for 60 min at RT with appropriate Alexa-conjugated secondary antibodies diluted in 2% NGS. Coverslips were mounted in Dako mounting media. All analyses were performed using a confocal laser scan microscope (Leica SP8 AOBS CLSM). The length of the myelin segment was determined by measuring MBP-positive segments that colocalized with NF-positive segments by using NeuriteTracer in ImageJ [44], for at least 20 myelin segments per experimental condition in 3 independent experiments.

2.8. In situ hybridization

OLGs were hybridized with 48 TMR labeled 20-nucleotide long probes designed against rat 14-kDa MBP, the major isoform present in rodent myelin [45]. Briefly, cells were fixed in 4% PFA and opened with ethanol, incubated overnight at 37ºC with 1 ng/µL probe mix in 10% formamide-containing hybridization buffer and washed with SSC (150mM NaCl, 15mM sodium citrate). Cells were subsequently blocked with BSA and incubation with primary anti-MBP and appropriate secondary antibodies as described above. Coverslips were mounted in Dako mounting medium and analyzed with a confocal laser scan microscope (Leica SP8 AOBS CLSM). For quantification of the cellular distribution see above.

2.9. Statistics

All data are represented as the mean ± SD of at least three independent experiments. Statistical significance was calculated by a two-tailed Student's t-test for comparison between two means and by one-way ANOVA followed by a Dunnet's posttest when more than two means were compared to the control group (untreated cells). A p value of $p<0.05$ was considered statistically significant.

3. Results

3.1. TNFα treatment induces shortening of myelin segments in myelinated cultures

TNFα is prominently present in MS lesions, and within the CSF, the levels of TNFα correlate with disease activity [1,2,6,7]. However, TNFα is also thought to be necessary for remyelination, and OPC proliferation in particular [17]. It is unknown whether TNFα has an effect on myelin membrane integrity. To asses such a potential effect, myelinated spinal cord cultures were employed. These spinal cord-derived cultures, plated on top of a feeding layer of astrocytes, represent an appropriate model system to study myelin maintenance, and approximately three weeks after plating, myelin segments can be clearly visualized by optical microscopy [38]. To examine the effect of TNFα on myelin stability, the myelinated cultures were exposed at 19 DIV to the cytokine at a relatively low concentration of 10 ng/ml (approx. 100 U/ml). At 26 DIV, the cultures were fixed and stained with the neurofilament marker NF-H to visualize axons, and with the myelin marker MBP to visualize myelin segments. As shown in Fig. 1, in TNFα-treated cultures, remarkable discontinuities between (arrows) and in the length of MBP-positive myelin segments ('internodes') were apparent, the internodal length as such being diminished on average by approx. 50%, relative to untreated cultures. Hence, this finding suggests that the length of existing myelin segments is susceptible to remodeling, being shortened upon exposure to TNFα. In these cultures all cells, including neurons, astrocytes and oligodendrocytes, harbor receptors for TNFα [46,47]. Therefore, we next examined in OLG monocultures whether the effect of TNFα on myelin membrane remodeling is due to a direct and/or indirect effect on oligodendrocytes.

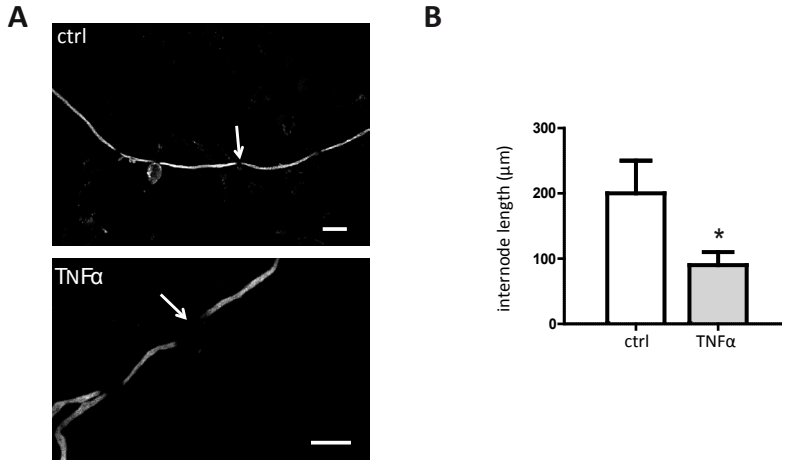

Figure 1: TNFα treatment induces shortening of myelin segments in myelinated cultures. At 19 days in vitro (DIV) embryonic rat myelinated spinal cord cultures plated on a

feeding layer of rat cortical astrocytes were untreated (ctrl) or treated with 10 ng/ml TNFα. A. Spinal cord cultures at 26 DIV were stained for MBP (myelin marker). Representative images are shown. Scale bar is 100 µm. B. Quantitative analysis of the length of the myelin segments (internodal length). Bar represents mean + SD of 3 independent experiments. Statistical difference with untreated (ctrl) cells as assessed with a Student's t-test (* $p<0.05$). Note that upon exposure of TNFα, the length of the MBP-positive myelin segments is significantly reduced.

3.2. TNFα treatment induces a reversible redistribution of MBP protein from myelin membranes towards primary processes

OLGs grown in monoculture follow the same developmental pattern as in the presence of neurons, i.e., all the myelin components are expressed in a coordinated fashion and transported to the different subdomains in the myelin sheet [29,33,48]. Therefore, mature OLGs represent a good in vitro model to study remodeling of myelin membranes. As direct exposure to TNFα may be toxic to OLGs in a concentration-dependent manner [20,21], we first exposed mature OLGs to different concentrations of TNFα ranging from 2 to 200 ng/ml. Cytotoxicity was determined by measuring the release of LDH into the culture medium, and cell viability with an MTT assay. At all concentrations tested, no significant effect of TNFα was apparent on LDH release and MTT activity relative to untreated cells (Supp. Fig. 1). Based on these findings, the concentration of 20 ng/ml of TNFα was used for all further experiments with OLG monocultures. To examine the effect of TNFα on myelin maintenance, mature OLGs were treated with TNFα, i.e., 7 days after initiating OPC differentiation, when the majority of the MBP-positive OLGs have synthesized a myelin sheet. As shown in Fig. 2A, following 3 days of exposure to TNFα, MBP protein was mainly localized to the cell body and primary processes, whereas in untreated OLGs MBP's localization was more pronounced in the myelin sheets. Indeed, the number of cells positive for MBP that bear MBP-positive membranous structures between the cellular process, i.e., sheets, was reduced upon TNFα treatment as compared to untreated mature OLGs (Fig. 2B). Western blot and qPCR analysis showed no significant difference in both MBP protein and mRNA expression levels, respectively (Supp. Fig. 2), indicating that the observed difference in MBP localization is not due to degradation or altered synthesis. To reveal a potential enrichment of MBP protein expression in cell body and primary processes upon exposure of mature OLGs to TNFα, we developed a method to quantify the cellular distribution of MBP per cell. Given the irregular shape of OLGs, 3 circular lines were manually drawn per cell, i.e., one around the cell body, the second one at the interface of the end of the primary process and the start of the myelin sheet, and the third one around the outer edge of the myelin sheet (Fig. 2C). To determine the relative cellular distribution of MBP in

each cell, the ratio between the fluorescent intensity of MBP in the myelin sheet, i.e., the area within the two outer circular lines and the fluorescence intensity of MBP in the cell body and the primary processes, i.e., the area within the two inner circular lines, was calculated. If the ratio exceeds a value of 1, MBP can be considered as to mainly localize to the outer myelin sheets and conversely, if the ratio was below 1, MBP is enriched in the cell body and primary processes. Applying this quantification method, we confirmed our visual observations that in TNFα -treated mature OLGs, MBP is significantly enriched in the cell body and primary processes, whereas in untreated cells MBP mainly localized to the myelin sheet (Fig. 2D).

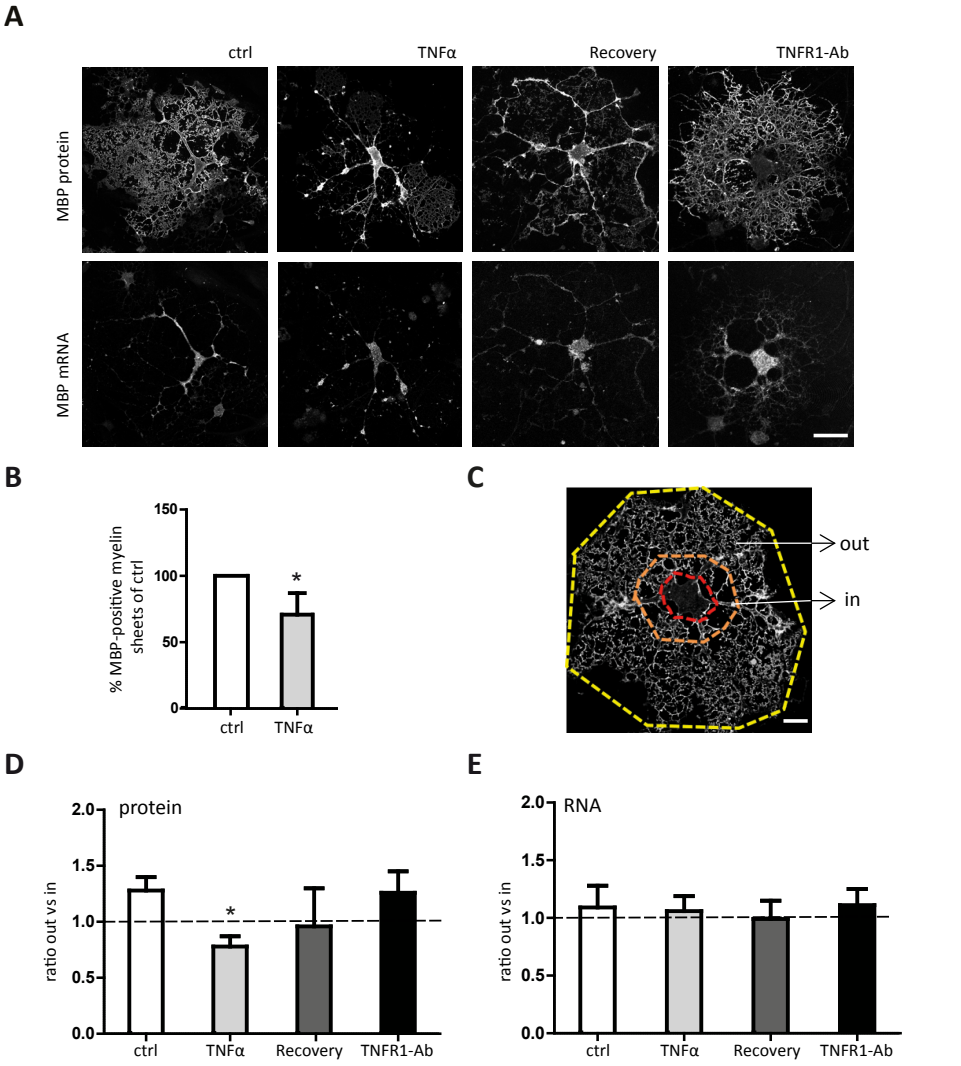

Figure 2: TNFα treatment induces a reversible redistribution of MBP protein towards primary

processes in mature oligodendrocytes.
Mature oligodendrocytes were left untreated (ctrl), treated with 20 ng/ml TNFα, or prior to treatment with TNFα pretreated with a blocking antibody against TFNR1 for 3 days, or allowed to recover from TNFα for 24 hrs (recovery). Cells were subjected to MBP mRNA probe labeling followed by immunocytochemistry for MBP protein. A. Representative confocal images of the localization of MBP protein and mRNA in the same cell. Scale bar is 20 µm. B. Quantitative analysis of the number of MBP-positive cells bearing myelin-like membranes. Each bar represents the mean + SD of 3 independent experiments. In each experiment, the data of untreated cells was set at 100%. Statistical difference with untreated (ctrl) cells as assessed with an one sample t-test (* $p<0.05$). C. Representative example of the quantification method to analyze MBP protein localization within a cell (see Materials and Methods for details). For each cell the ratio of the intensity of the protein (or mRNA) in the outer myelin membrane ('out') vs the intensity of the protein in the cell body and primary processes ('in') is determined. A ratio above 1 indicates an enrichment in myelin-like membranes. Scale bar is 10 µm. D,E. Quantitative analysis of the localization of MBP protein (D) and mRNA (E) as described at C. Each bar represents the mean + SD of 3 independent experiments. In each independent experiment 15 cells per condition were analyzed. Statistical difference with untreated (ctrl) cells as assessed with an one-way ANOVA (* $p<0.05$, Dunnet's posttest). Note that TNFα induces a reversible retraction of MBP protein from myelin sheet towards cell body and primary processes, likely by activation of TNFR1.

Intriguingly, when the cells were allowed to recover for 24 hrs after 3 days of exposure to TNFα, MBP protein was prominently localized to the myelin sheets, and indistinguishable from untreated cells (Fig. 2A and D), indicating that the effect of TNFα is reversible. Moreover, the effect of TNFα wasmediated by TNFR1, since a functional blocking antibody directed against TNFR1 counteracted the effect of TNFα on MBP localization (Fig. 2A and D). Hence, these results suggest that the TNFα -mediated ectopic localization of MBP in the cell body and primary processes of mature OLGs might be a reversible reallocation of already synthesized MBP protein towards to the cell body and primary processes. Of interest, MBP mRNA was similarly distributed in untreated and TNFα -treated mature OLGs, being localized deep into the processes (Fig. 2A and E), indicating that the enrichment of MBP protein in cell body and primary processes upon TNFα treatment was likely not due to impaired MBP mRNA trafficking. Given the difference in localization pattern of MBP upon treatment with TNFα, we next examined the lateral membrane organization of MBP.

3.3. Galactosylceramide is enriched in TX-100 resistant microdomains upon TNFα treatment

In spite of its nature as a peripheral membrane protein, MBP does associate with detergent resistant microdomains, termed 'lipid rafts', upon OLG maturation [49,50]. Therefore, given the apparent redistribution of MBP following TNFα treatment, we next analyzed whether this redistribution of MBP is also reflected by a lateral reorganization of MBP's association with membrane microdomains. Previous findings have revealed that CHAPS-resistant membrane microdomains are prevalent in myelin

membranes (reviewed in [51]), while TX-100-resistant domains are more enriched at the cell body and primary processes (chapter 3). Therefore, given the observed TNFα -induced redistribution of MBP from the sheet towards cell body and primary processes, we first isolated membrane microdomains by TX-100 detergent extraction followed by OptiPrep density gradient centrifugation and Western blot analysis. Of the obtained 7 fractions, fractions 3 and 4 are considered as raft fractions, whereas TX-100 soluble proteins appear in fractions 6 and 7 [39]. MBP is prominently present in TX-100-resistant membrane microdomains in both untreated and TNFα -treated mature OLGs (Fig. 3A,B, 49.4±13.0% and 47.2±5.2% respectively). Similarly, irrespective of TNFαtreatment, no change was apparent in the distribution of MBP in CHAPS-resistant microdomains (data not shown). Galactosylceramide (GalC), a lipid typically present at the extracellular leaflet of the lipid bilayer, including the myelin membrane, plays a major role in the lateral membrane association of MBP, localizing at the cytoplasmic face of the membrane [50,52–56]. Remarkably, following TNFα treatment, GalC became relatively enriched in TX-100-resistant membrane microdomains (Fig. 3A,C, fractions 3-4), with a concomitant decrease in non-raft fractions (Fig. 3A,C, fractions 6-7). Interestingly, following TNFα treatment, the glycolipid appears to be clustered at the cell body plasma membrane and primary processes, as visualized with the anti-GalC antibody O1 (Fig. 4). Hence, TNFα alters the lateral organization of GalC, and induces its partial clustering, particularly in the processes, which seems to reflect the appearance of MBP at similar conditions (cf. Fig. 2A). However, these findings still do not explain the underlying mechanism as to why MBP in mature OLGs redistributes from myelin membranes towards cell body and primary processes upon exposure to TNFα.

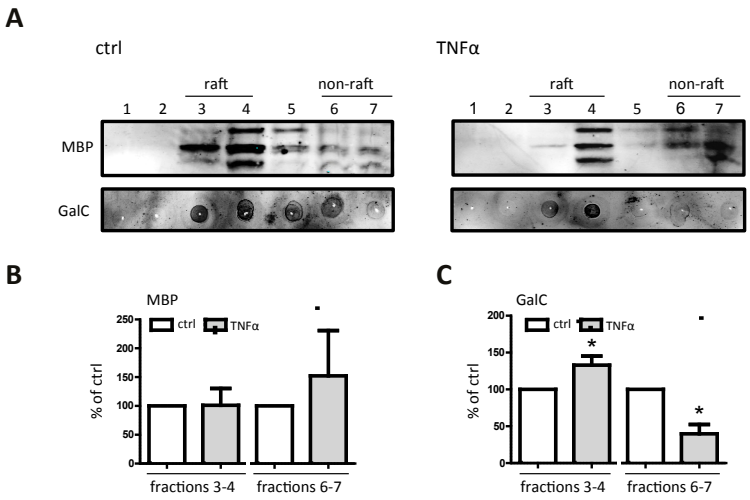

Figure 3: Galactosylceramide is enriched in TX-100 resistant microdomains upon TNFα treatment.
Mature oligodendrocytes were left untreated (ctrl) or treated with 20 ng/ml TNFα for 3 days. The presence of MBP (A,B) and GalC (A,C) in membrane microdomains was analysed by TX-100 detergent extraction followed by OptiPrep density gradient centrifugation and Western (A,B) or dotblot (A,C) analysis. Representative blots of 3 independent experiments are shown. The total protein/lipid expression was calculated by adding the intensity of all the fractions. The protein/lipid percentage of each fraction was then calculated by dividing the protein intensity present in that fraction by total protein/lipid expression. Bar graphs of the pooled fraction percentage of (raft) fractions 3 and 4 and (non-raft) fractions 6 and 7 of MBP (B), GalC (C), relative to untreated cells (ctrl, set at 100% in each experiment) are shown. In untreated cells, 49.4±13.0% of MBP and 43.3±21.2% of GalC were present in fractions 3 and 4, and 25.8±5.9% of MBP and 43.7±28.4% of GalC in fractions 6 and 7. Statistical difference with untreated (ctrl) cells as assessed with an one sample t-test (* $p<0.05$). Note that upon TNFα treatment GalC, but not MBP, is enriched in TX-100-resistant membrane microdomains, while a contaminant significant decrease in the non-raft fractions was noticed

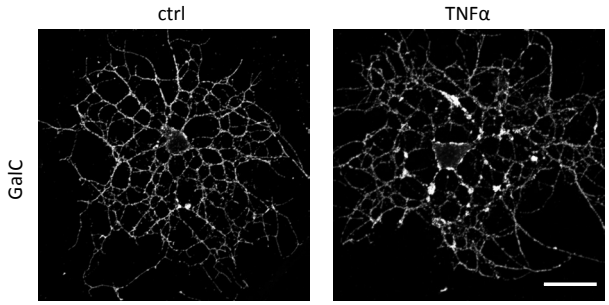

Figure 4: TNFα treatment alters the localization of galactosylceramide.
Mature oligodendrocytes were left untreated (ctrl), or treated with 20 ng/ml TNFα. After 3 days, the surface localization of GalC was assessed using immunocytochemistry on live cells (O1 antibody). Scale bar is 20 µm. Note that upon TNFα treatment GalC appears as clusters at the plasma membrane of the cell body and primary processes.

3.4. TNFα treatment disrupts the actin cytoskeleton in mature oligodendrocytes

To further examine the underlying mechanism of the redistribution of MBP upon TNFα treatment, we considered a potential involvement of the cell's cytoskeleton. Previous studies have shown that TNFα induces changes in cytoskeletal structures [57–59], and that MBP interacts with the cytoskeleton [60–62]. Also, a connection between raft localization and cytoskeleton has been proposed [63]. In OLGs, the cytoskeleton consists of tubulin and actin filaments, while it lacks intermediate filaments [64]. In control mature OLGs, actin filaments, visualized with fluorescently-labeled phalloidin, are predominantly present in the processes as well-structured long filaments (Fig. 5A). In TNFα -treated cells, this well-structured pattern of actin filaments is lost, revealing a diffuse distribution of apparently smaller

filaments in secondary and tertiary process, but remarkably not in the cell body and primary processes. Quantitative analysis showed that the number of cells with this diffuse distribution pattern of actin filaments was increased in TNFα -treated cells as compared to untreated mature OLGs, which was reversed 24 hrs after TNFα withdrawal (Fig. 5A and B), indicating that the actin cytoskeleton is not irreversibly damaged. Importantly, in both untreated and recovered cells MBP and actin co-localized. The (partial) co-localization was lost when mature OLGs were exposed to TNFα, indicating an uncoupling of MBP and the actin cytoskeleton. Immunocytochemical analysis of the tubulin cytoskeleton using an antibody against β-tubulin revealed virtually no difference in the localization of tubulin (Supp. Fig. 3); tubulin is primarily present in the primary processes, in both TNFα -treated and untreated cells. Therefore, these results indicate that TNFα reversibly disrupts the actin, but not tubulin cytoskeleton in mature OLGs. Given the uncoupling of MBP and actin upon TNFα treatment and the fact that actin may serve as a stabilizer of distinct membrane microdomains [65,66], we next examined whether the lateral movement of MBP towards the cell body and primary processes was actin-dependent upon TNFα treatment.

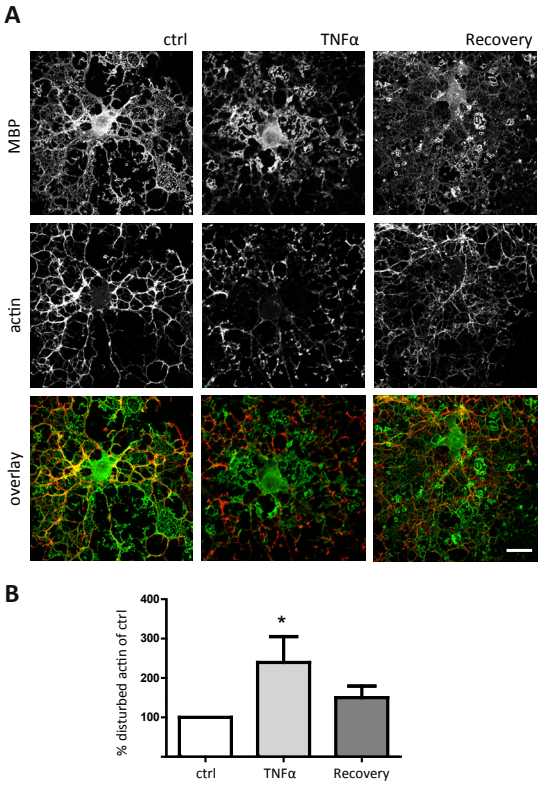

Figure 5: TNFα treatment disrupts the actin cytoskeleton in mature oligodendrocytes.
Mature oligodendrocytes were left untreated (ctrl), treated with 20 ng/ml TNFα, for 3 days, or allowed to recover from TNFα for 24 hrs (recovery). Cell were subjected to MBP immunocytochemistry (green), followed by visualization of actin filaments with TRITC-conjugated phalloidin. Representative confocal images (A) are shown. Scale bar is 20 µm. The appearance of the actin cytoskeleton of at least 100 cells was scored and characterized as organized or disorganized (B). Each bar represents the mean + SD of 3 independent experiments. In each experiment, the data of untreated cells was set at 100%. Statistical difference with untreated (ctrl) cells as assessed with an one-way ANOVA (* $p<0.05$, Dunnet's posttest). Note that upon TNFα treatment the actin cytoskeleton is disordered into apparently smaller filaments in secondary and tertiary processes

3.5. TNFα treatment alters MBP's microdomain association from actin-dependent to actin-independent

Previous studies revealed that detergent fractionation at 4°C may create artefacts with regard to a protein's distribution in the gradient, particular when it associates with the cytoskeleton. To examine whether the TNFα-mediated change in the cellular localization of MBP was actin-dependent, we applied a detergent-free raft isolation method that separates actin-dependent and actin-independent membrane microdomains [40]. Upon detergent-free OptiPrep gradient fractionation, fractions 1 and 2 are the very light fractions and represent membrane microdomains with a high lipid to protein ratio. The association of proteins in these membrane microdomains is sensitive to latrunculin B treatment [40], and fractions 1 and 2 are therefore considered as actin-dependent rafts. Fractions 3 and 4 also represent membrane microdomains, given the high lipid to protein ratio, and are characterized as actin-independent membrane microdomains. Proteins that are not present in membrane microdomains appear in fractions 7-9. As shown in Fig. 6A, in control mature OLGs, approx. 55% of the MBP fraction resided in fractions 1 and 2, i.e., in actin-dependent membrane microdomains. By contrast, TNFα treatment significantly reduced the actin-dependent membrane microdomain association of MBP (Fig. 6B). In fact, MBP became associated with actin-independent membrane microdomains, given its abundant and increased presence in fractions 3 and 4 (Fig. 6A and B). Furthermore, TNFα treatment also reduced the levels of actin and GalC in fractions 1-2 (Fig. 6A and C, D) without a concomitant increase in fractions 3-4, suggesting a redistribution tonon-raft membranes. Hence, TNFα treatment perturbed the integrity of the actin cytoskeleton in mature OLGs, which correlates with a segregation of MBP from actin-dependent to actin-independent membrane microdomains. In addition to its function as a molecular membrane glue, MBP also acts as a molecular barrier for proteins to enter the myelin membranes. Therefore, we next examined functional consequences of TNFα -induced reallocation of MBP with regard to the localization of other myelin proteins.

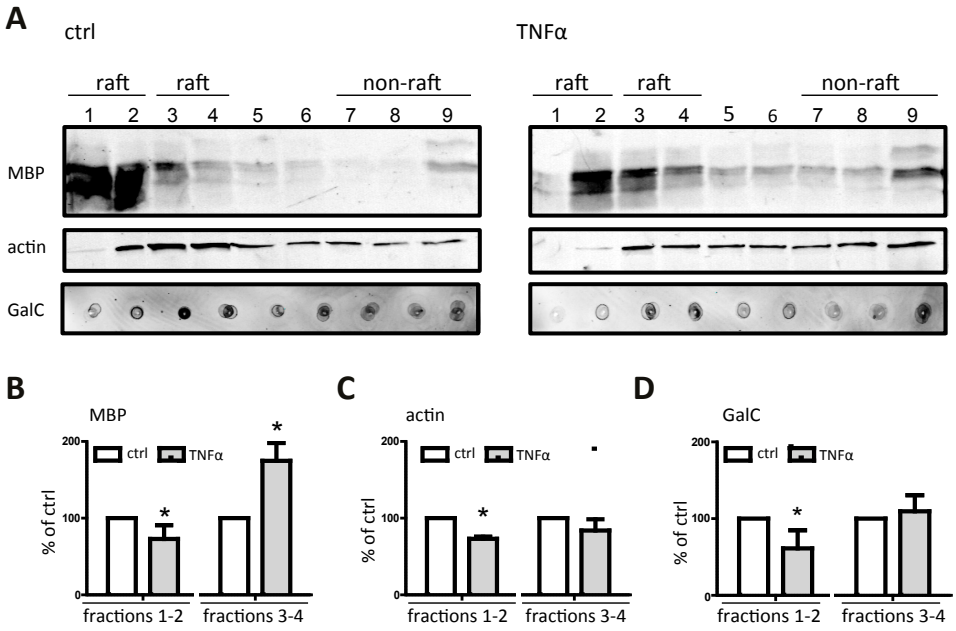

Figure 6: TNFα treatment alters MBP's microdomain association from actin-dependent to actin-independent.
Mature oligodendrocytes were left untreated (ctrl) or treated with 20 ng/ml TNFα for 3 days. The presence of proteins (A-C, MBP, actin) and GalC (A,D) in membrane microdomains isolated in a detergent-free manner in combination with OptiPrep density gradient centrifugation, and Western (MBP, actin) or dotblot (GalC) analysis. Representative blots of 4-5 independent experiments are shown. The total protein/lipid expression was calculated by adding the intensity of all the fractions. The protein/lipid percentage of each fraction was then calculated by dividing the protein intensity present in that fraction by total protein/lipid expression. Bar graphs of the pooled fraction percentage of actin-dependent raft fractions 1 and 2 and actin-independent raft fractions 3 and 4 of MBP (B), actin (C) and GalC (D) relative to untreated cells (ctrl, set at 100% in each experiment) are shown. In untreated cells, 56.0±12.1% of MBP, 27.9±20.9% of actin and 23.2±4.7% of GalC were present in fractions 1 and 2, and 19.3±0.6% of MBP, 25.1±3.7% of actin and 29.5±4.4% of GalC in fractions 3 and 4. Statistical difference with untreated (ctrl) cells as assessed with an one sample t-test (* $p<0.05$). Note that upon TNFα treatment MBP redistributed from actin-independent membrane microdomains (A, B, fractions 1-2) to actin-dependent membrane microdomains (A, B, fractions 3-4).

3.6. TNFα treatment interferes with the localization of myelin proteins PLP and CNP

Proteolipid protein (PLP) and 2',3'-cyclic-nucleotide 3'-phosphodiesterase (CNP) are myelin specific proteins, showing a distinct localization in myelin; PLP is present in compact myelin, facilitating the apposition of the extracellular leaflets of the different myelin membrane wraps [67,68], whereas CNP is abundantly present in non-compact myelin, and has been identified as a factor that delays myelin compaction during

development [69]. In cultured untreated mature OLGs, PLP is present in the cell body, primary processes and myelin sheets, while CNP expression is more restricted to the cell body and primary processes (Fig. 7A and B). Following cellular treatment with TNFα for three days, PLP mainly localizes in the cell body and primary processes, while the protein is nearly absent from the myelin sheet (Fig. 7A and C). In contrast, CNP was more evenly distributed in the cells following TNFα exposure (Fig. 7B and D). Hence, TNFα treatment perturbs the organized structure of myelin specific proteins within mature OLGs, and therefore likely the compaction, which might allow for remodeling and shortening of existing myelin membranes (Fig. 1).

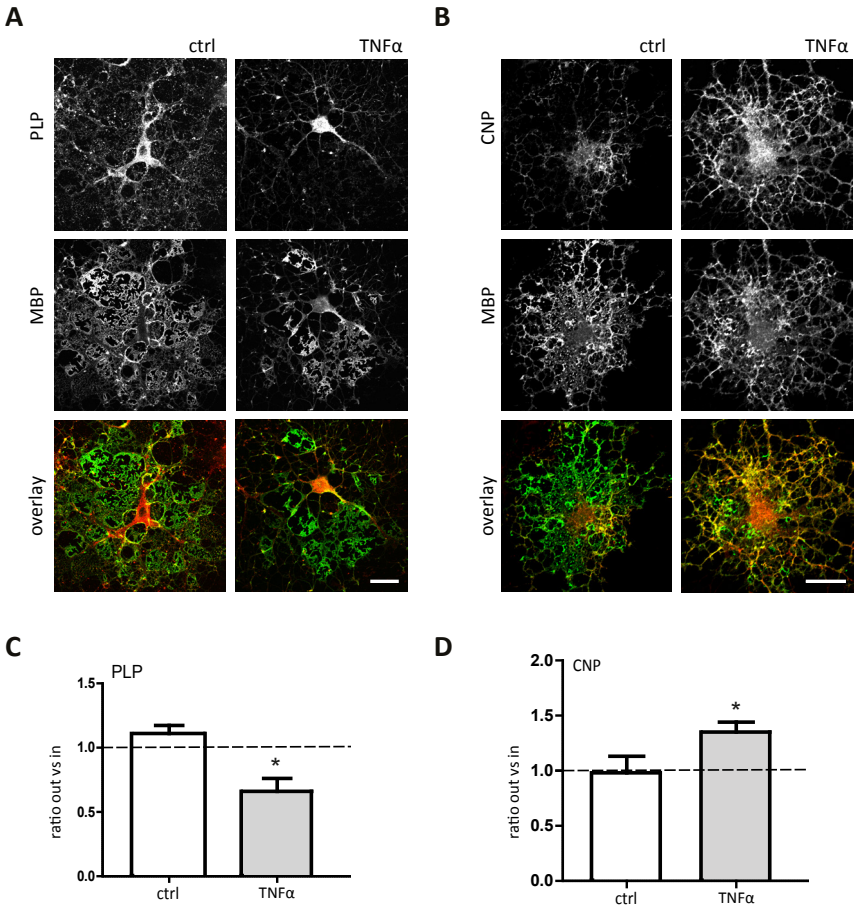

Figure 7. TNFα treatment interferes with the localization of myelin proteins PLP and CNP. Mature oligodendrocytes were left untreated (ctrl) or treated with 20 ng/ml TNFα for 3 days. Cells were subjected to double immunocytochemistry for MBP (green) and either PLP (A, C, red) or CNP (B, D, red). Representative confocal images are shown. Scale bar is 20 µm. Quantitative analysis of the localization of PLP (C) and CNP (D) was performed as described in Materials and Methods (see also Fig. 1C). Each bar represents the mean + SD of 3 independent experiments. In each independent experiment 15 cells per condition were analyzed. Note that

TNFα induces a retraction of PLP from myelin membranes towards primary processes, while CNP was more evenly distributed upon TNFα treatment.

4. Discussion

Upon CNS demyelination, extrinsic factors such as extracellular matrix proteins and pro-inflammatory cytokines contribute to tissue repair. However, their persistent presence may be detrimental as observed for example in MS, where OLG apoptosis, demyelination and/or impaired remyelination may occur. In this context, we examined the effect of pro-inflammatory cytokine TNFα on myelin membrane integrity and stability. Our findings revealed that long-term treatment with TNFα induced a remarkable decrease in the length of myelin segments, and a lateral redistribution of MBP from the sheet towards cell body and primary processes in cultured mature OLGs. A similar enrichment of MBP in OLG cell bodies was reported following treatment of neuron-OLG co-cultures with TNFα [70]. In mature OLGs, TNFα treatment resulted in a perturbed actin cytoskeleton along with the dissociation of MBP from actin-dependent membrane microdomains. The effect of TNFα was not cytotoxic, reversible upon TNFα withdrawal, and likely mediated by interaction of the cytokine with TNFR1. Indirectly, our data also support the notion that MBP may act as a molecular barrier for other myelin proteins [29] given that TNFα exposure caused a concomitant redistribution of PLP towards primary processes and a reallocation of CNP towards the myelin sheets. The in vivo significance of these data may relate to a beneficiary effect of, transiently present TNFα during remyelination, providing the necessary elasticity to existing myelin membranes, allowing the intercalation of newly formed myelin segments and paranodes to be ‘reconstructed’.

Upon TNFα treatment, the length of the MBP-positive internodes significantly decreased in myelinated cultures, indicating that the internodes permit remodeling of existing myelin segments when necessary. In this context it was recently demonstrated that in the adult brain myelin segments may remodel and that the length of internodes shorten with age [71]. To shorten myelin segments, myelin decompaction has to occur, which requires a reallocation of myelin proteins and lipids. The present study suggests that the presence of TNFα might be a key feature in triggering and/or facilitating such a decompaction. Thus, in mature OLGs the presence of TNFα caused a lateral dislocation of MBP from myelin membranes towards the cell body and primary process. The concomitant redistribution of MBP from actin-dependent to actin-independent membrane microdomains may be instrumental in the overall mechanism of decompaction, its occurrence being supported by an altered localization of other myelin components, such as PLP and CNP, presumably reflecting

the relief of MBP's barrier function [29].

It remains to be determined whether the perturbation of the actin cytoskeleton is a direct effect of TNFα treatment or a secondary response of MBP's lateral redistribution to actin-independent membrane microdomains. A direct effect of TNFα on actin filaments has been observed in other cell types [57–59]. Furthermore, upon actin cytoskeleton disruption by cytochalasin B, both MBP and GalC are mislocalized [55,72]. A TNFα -mediated disruption of the actin filaments may thus lead to an uncoupling of MBP and the actin cytoskeleton, resulting into the lateral redistribution of MBP to actin-independent membrane microdomains, and the retraction of MBP towards cell body and primary processes. As a consequence, GalC might redistribute to TX-100-resistant membrane microdomains. Indeed, alterations in the lipid environment of MBP at the inner leaflet may result in clustering of GalC at the extracellular leaflet of the membrane [54]. In favor of a secondary, i.e., indirect effect of TNFα treatment on a perturbed actin cytoskeleton is the observation that MBP interacts with the actin cytoskeleton at the membrane surface [60], and that OLGs, in the absence of functional MBP, display a punctuated actin cytoskeleton [73]. Furthermore, MBP can undergo various posttranslational modifications, including methylation, phosphorylation, and deimination [26], the latter two being able to modulate MBP-mediated assembly of actin [60]. Thus, phosphorylation and deimination of MBP may decrease the ability of MBP to link actin to the membrane surface. In fact, we have noticed a slight decrease in the total levels of phosphorylated MBP upon long-term TNFα treatment (our unpublished observations). However, whether TNFα altered the deimination, or induced other reported posttranslational modifications of MBP remains to be determined. It is also possible that TNFα treatment leads to a segregation of GalC into TX-100-resistant membrane microdomains. This redistribution of GalC at the extracellular leaflet of the membrane may mediate a concomitant redistribution of MBP at the inner leaflet (chapter 4), thus resulting in uncoupling of MBP and the actin cystoskeleton, and hence a perturbed actin cytoskeleton. Indeed, GalC plays a major role in the lateral membrane localization of MBP, i.e., antibody-mediated clustering of GalC alters the distribution of MBP and the actin cytoskeleton [55]. Clearly, these considerations on the exact scenario of events upon TNFα treatment leading to myelin membrane shortening warrants further investigations.

Upon injury in healthy CNS, TNFα is only transiently secreted, and at those conditions its role is likely beneficiary for TNFR2-mediated OPC proliferation in relation to remyelination [17] and, as shown here, TNFR1-mediated remodeling of existing myelin segments. However, in MS and other inflammatory demyelinating diseases, the level of TNFα is persistently increased [74]. Upon 'natural' remyelination,

myelin sheaths are still in the process of internodal elongation during axonal enwrapment and compaction [69]. Yet, at disease conditions, reflected by the persistent presence of TNFα, the described lateral reallocation of myelin components in conjunction with the perturbed actin cystoskeleton might preclude the compaction of newly formed myelin sheaths, thus contributing to remyelination failure when present persistently. Indeed, our preliminary results suggest that TNFα treatment of developing OLGs and myelinating cultures for 14 days, exert similar effects as shown here for mature OLGs and myelinated cultures, further emphasizing the necessity to reduce TNFα -actions at later stages of the remyelination process.

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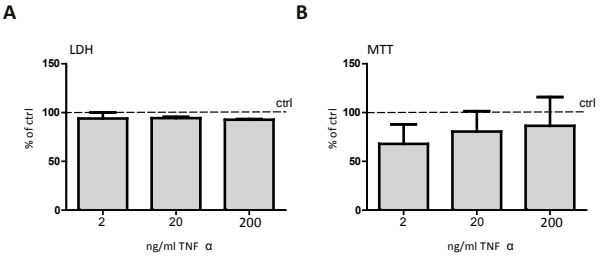
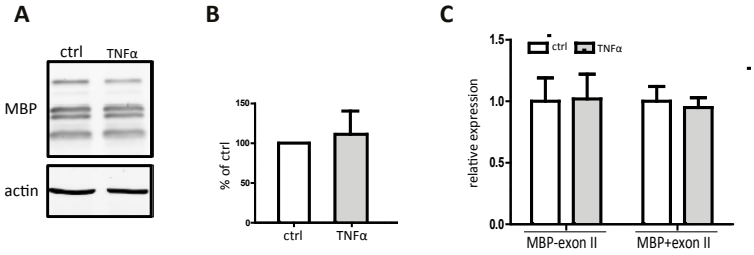
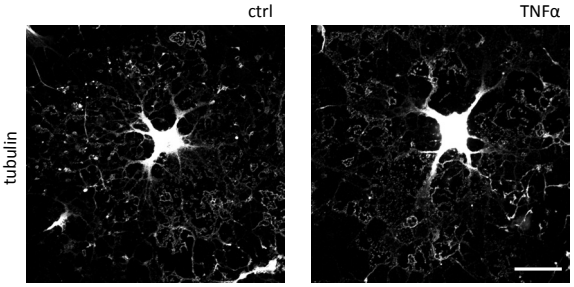
Supplementary Figures



Supplementary Figure 1: TNFα is not toxic to mature oligodendrocytes.
Mature oligodendrocytes were left untreated (ctrl), or treated with 2, 20 or 200 ng/ml TNFα. After 3 days, LDH (A) and MTT (B) assays were performed. Each bar represent the mean + SD of the relative cytotoxicity (A) and viability (B) to untreated (ctrl, horizontal line) cells. Statistical analysis were performed with an one sample t-test.



Supplementary Figure 2: TNFα treatment does not alter MBP protein and mRNA levels.
Mature oligodendrocytes were left untreated (ctrl), or treated with 20 ng/ml TNFα for 3 days. A, B. Cell lysates were analysed for protein levels of MBP and actin. Representative blots are shown (A). Expression of MBP, as a ratio of actin, was quantified relative to that of untreated cells (ctrl), which were set at 100% in each experiment (B). Each bar represent the mean + SD of 3 independent experiments. Statistical analysis were performed with an one sample t-test. C. Cells were subjected to real time qPCR analysis using specific primers for MBP isoforms with and without exon-II. mRNA expression was normalized to the house-keeping genes HMBS and HPRT1. Bars depict mean + SD of 3 independent experiments. Statistical analysis were performed with an one sample t-test. Note that upon 3 days exposure to TNFαthe protein and mRNA levels of all MBP postnatal isoforms remain unaltered.



Supplementary Figure 3: TNFα treatment appears not to affect the tubulin cytoskeleton.
Mature oligodendrocytes were left untreated (ctrl), or treated with 20 ng/ml TNFα . After 3 days, the tubulin cytoskeleton was visualized by immunocytochemistry (anti-β-tubulin). Scale bar is 20 µm.