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Transcriptional expression of MBP in oligodendrocytes depends on functional syntaxin 4; a potential correlation with autocrine signalling

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ABSTRACT

Myelination of axons by oligodendrocytes is essential for saltatory nerve conduction. To form myelin membranes, a coordinated synthesis and subsequent polarized transport of myelin components is necessary. Here we show that as part of the mechanism to establish membrane polarity, oligodendrocytes exploit a polarized distribution of the SNARE machinery components syntaxins 3 and 4, localizing to the cell body and the myelin membrane, respectively. Our data further reveal that the expression of MBP, a myelin-specific protein that is synthesized 'on site' after transport of its mRNA, depends on the correct functioning of the SNARE machinery, which is not required for mRNA granule assembly and transport *per se*. Thus, downregulation and overexpression of syntaxin 4, but not syntaxin 3, in oligodendrocyte progenitor cells, but not immature oligodendrocytes, impeded MBP mRNA transcription, thereby preventing MBP protein synthesis. The expression and localization of another myelin-specific protein, PLP, was unaltered. Strikingly, conditioned medium obtained from developing oligodendrocytes was able to rescue the block of MBP mRNA transcription in syntaxin 4-downregulated cells. These findings indicate that the initiation of the biosynthesis of MBP mRNA relies on a syntaxin 4-dependent mechanism, which likely involves activation of an autocrine signalling pathway.

INTRODUCTION

During myelination oligodendrocytes (OLGs) express large quantities of myelin proteins and lipids that are subsequently transported from the cell body via processes to myelin membranes, which are wrapped around axons to form the myelin sheath. Like the apical and basolateral plasma membrane domains in polarized epithelial cells, the myelin-like membrane (sheet) and cell body plasma membrane can be considered as representing a reflection of the polarized nature of cultured OLGs⁹. Indeed, in previous work we observed that distinct viral proteins, i.e., the hemagglutinin (HA) of influenza virus and the glycoprotein of vesicular stomatitis virus (VSV G), which are sorted and transported in epithelial cells to the apical and basolateral domains, respectively, also display a distinct and preferential localization in cultured OLGs¹¹⁴. In fact, vesicular traffic to the myelin sheet relies on a basolateral-like, rather than an apical-like transport and sorting mechanism and similar basolateral sorting signals as in epithelial cells target proteins to myelin sheets^{115,194–196}. Of interest, vesicle-mediated transport does not occur in compact myelin, but rather proceeds via lateral membrane diffusion³², suggesting that once myelin is established, polarization is maintained in a non-vesicular manner.

From studies on polarized epithelial cells, it is known that a distinct membrane composition is established by polarized transport of membrane constituents. The final step in vesicular transport of membrane proteins involves the docking and fusion of a vesicle with its target membrane, which is mediated by a protein family referred to as SNAREs (soluble N-ethylmaleimide-sensitive factor attachment protein receptors)^{119,197,198}. The SNARE proteins are integral membrane proteins that are present on both the vesicles (v-SNARE) and the target membranes (t-SNARE). Importantly, the apical and basolateral plasma membrane domains of polarized epithelial cells contain distinct t-SNAREs¹⁹⁹, i.e., syntaxins 3 and 4, which are preferentially localized at the apical and basolateral plasma membrane, respectively^{176–178,200–202}. Both syntaxin 3 and syntaxin 4 are known to be present in OLGs^{9,39,179}, but their functional role in myelin biogenesis is still largely unknown. Therefore, in this work, we examined whether syntaxins 3 and 4 are functionally expressed in rat primary OLGs, and involved in myelin biogenesis, thereby focusing on the role of myelin sheet localized syntaxins and the two major myelin proteins, myelin basic protein (MBP) and proteolipid protein (PLP). These proteins are expressed in a timely fashion, and sorted and transported to the myelin membrane by different mechanisms^{9,29,203}. MBP, located at the cytoplasmic surface of myelin membranes, is a basic, membrane-associated adhesive protein, and essential for myelination *in vivo*^{204–206}. Its adhesive properties organize the close apposition of the inner membrane leaflets leading to myelin compaction²⁰⁷, essential for saltatory nerve conduction. Furthermore, MBP appears to act as a portal for protein entry into myelin membranes³². MBP is transported to the myelin sheath in its mRNA form^{12,13}, which is thought to circumvent premature adhesion of membranes^{9,204,206,207}. Although MBP mRNA is assembled in non-membranous granules^{12–14}, a causal relationship with the vesicular transport machinery is likely, given that membrane trafficking appears to be involved in RNA transport and/or anchoring^{208–210}. In contrast, PLP is an integral membrane protein that is synthesized at the endoplasmic reticulum, and

subsequently processed by vesicular transport, reaching the myelin membrane via a transcytotic transport mechanism^{8,25,139,211}. Furthermore, a distinct role for the v-SNAREs VAMP7 and VAMP3, cognate binding partners of syntaxin 3 and 4, respectively, in PLP trafficking has been recently demonstrated⁸. PLP plays a major role in assembly and stabilization of the myelin sheath in that the protein brings about the correct apposition of the extracellular leaflets of the membrane^{30,212}.

Here, we report that syntaxins 3 and 4 are functionally expressed in rat primary OLGs, and distribute in a polarized manner, syntaxin 3 being largely restricted to the cell body, whereas syntaxin 4 is upregulated during OLG differentiation, and locates towards the myelin sheet. Surprisingly, our findings further indicate that MBP mRNA transcription, but not MBP mRNA trafficking, depends on functional expression of syntaxin 4, but not syntaxin 3, whereas trafficking of PLP to the myelin membrane proceeds independently of syntaxin 4. The intimate involvement of syntaxin 4 in initiating MBP mRNA expression in oligodendrocyte progenitor cells (OPCs) is supported by the lack of effect of downregulation of syntaxin 4 in immature OLGs, while the effect was reversed by conditioned medium of developing OLGs. This data is taken to suggest that syntaxin 4-mediated autocrine signalling at the onset of OPC differentiation is necessary for initiating MBP mRNA transcription, preceding its granule-mediated transport to the myelin membrane. This insight will aid in developing novel approaches towards inducing remyelination in demyelinating pathologies, such as multiple sclerosis.

MATERIALS AND METHODS

Cell cultures

Primary oligodendrocytes: Primary OLG cultures were generated by a shake-off procedure as described previously^{112,213}. 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) at 30,000 cells per well (500 µL), and for conditioned medium, qPCR, Western blot and co-IP analysis on PLL-coated 10-cm dishes (Nalge Nunc International, Roskilde, Denmark) at 106 cells per dish (6 mL or 4.5 mL for conditioned medium). After 48 hrs, differentiation was induced by growth factor withdrawal, and cells were cultured in SATO medium supplemented with 0.5% FCS (Bodinco, Alkmaar, The Netherlands) for 3 days (immature OLGs) or 10 days (mature OLGs). Conditioned medium of developing OLGs was collected 3 days after initiating differentiation, and used in a 1:1 ratio with fresh medium (SATO with 0.5% FCS).

Myelinating co-cultures: Primary rat dorsal root ganglion neurons (DRGNs) were isolated from 15-day-old Wistar rat embryo's (Harlan, the Netherlands), as described before, with minor modifications²¹⁴. Dissociated DRGNs were plated as 40 µL drops at a density of 60,000 cells on 13-mm coverslips (0.5 mL) that were pre-coated with PLL (10 µg/mL), followed by growth-factor-reduced matrigel (1:40 dilution; BD Bioscience, Bedford, MA). DRGNs were cultured in 500 µL of neurobasal medium (Invitrogen, Paisly, UK) supplemented with 2% B27 (Invitrogen) in the presence of nerve growth factor (NGF, 100 ng/mL; Serotec, Kinglington, UK). Fibroblasts were eliminated with two 48 hrs cycles of 10 µM 2'-deoxy-5-fluorouridine (FdU, Sigma) 1 and 5 days after plating of the DRGNs. OPCs were seeded onto 14-19 div DRGNs at a 1.5:1 ratio in Basal Medium Eagle (BME, Invitrogen) supplemented with 1% ITS supplement (Sigma), 0.25% FCS, and D(+)-glucose (4 mg/mL, Sigma), after which the co-cultures were maintained for 14 days. All experimental procedures were approved of by the Animal Ethical Committee of the UMCG.

Constructs and primers

shRNA: Syntaxin 3, syntaxin 4, and VAMP3 shRNA constructs were designed with DSIR²¹⁵, resulting in the following target sequences: 5'-acaaaGGCGCGCCACGAAAGAAATTGATAATTAACCTCGAGATAATTATCAATTTCTTTTCG GTTTTTCTCCTGCAGGcaca-3' (shRNA against rat syntaxin 3), 5'-acaaaGGCGCGCCAGGTGTTTGTGTCTAATATAACTCGAGATATATTAGACACAAACACCGTTTTTTCTCCTGCAGGcaca-3' (shRNA against rat syntaxin 4), and 5'-acaaaGGCGCGCCACGGAGATGTTCACTTTCTAACTCGAGATA GAAAGTGAACATCTCCGGTTTTTTCTCCTGCAGGcaca-3' (shRNA against rat VAMP3). With restriction enzymes *AscI* and *SbfI*, shRNA constructs were cloned into the lentiviral

vector pHR^{trip}-eGFP (Addgene) or with LR clonase in pLenti-x2 Puro DEST (Addgene). Correct insert of the construct was confirmed by DNA sequencing.

Overexpression: The cDNA encoding syntaxins 3 or 4 were a kind gift of dr. Thomas Weimbs (University of California Santa Barbara, CA, ²⁰¹). For cloning the syntaxin genes in the retroviral vector pLXIN (Clontech Biosciences, Mountain View, CA), an XhoI restriction site at the ATG start codon of the syntaxin 3 and syntaxin 4 gene and a XhoI restriction site after the stop codon of both genes were introduced by PCR. The following primers were used: 5'-CATGTATTTCGAAGAGCTCTTCGCACATGG-3' (forward syntaxin 3), 5'-CTAGGTGATCAAGAGCTCCTAGGGCCCACG-3' (reverse syntaxin 3), 5'-CGAATAGCTATGAGCTCCATGGTCTAG-3' (forward syntaxin 4) and 5'-GATCTCCTAGAGCTCACGTAGGGAC-3' (reverse syntaxin 4). The PCR product was digested with XhoI (Invitrogen) and ligated with the 1.8 kb retroviral vector pLXIN. The orientation and the integrity of the obtained pLXIN constructs were confirmed by DNA sequencing.

Production of viral particles and cell transduction

Lentiviral: For production of lentiviral particles, the constructs, packaging, and envelope plasmids (pRSV-Rev and pMD.G) were transfected into the HEK293T packaging cell line using calcium phosphate. Two days after transfection, cells were washed with 0.01 M phosphate-buffered saline (PBS), conditioned media collected after 24 h, filtered through a PVDF membrane-based filter (Millipore, 0.45 µm pore size), and either used immediately or stored frozen at -80°C. Cells were transduced before shake off for co-culture experiments or at the indicated developmental stage in monocultures for 6-8 hrs with lentiviral particles, two times diluted in medium supplemented with 4 µg/mL hexadimethrine bromide (polybrene; Sigma). For qPCR experiments of OLG monocultures, transduced OPCs were selected in SATO medium supplemented with FGF-2, PDGF-AA, and 0.25 µg/ml puromycin (Sigma) G418 during 5 days. After selection the cells were cultured in SATO with 0.5% FCS for 7 days.

Retroviral: The production of retroviral particles and the subsequent infection of OPCs were performed according to Ref. 216. Briefly, for production of recombination-deficient retroviruses, the constructs were transfected into the GP+E86-packaging cell line (Genetix Pharmaceuticals, Inc. Cambridge, MA), using the FuGENE 6 transfection reagent. Two days after transfection, cells were collected, diluted 5-fold and cultured under selection in packaging cells medium supplemented with 1 mg/mL G418 until resistant clones appeared (70% confluent). The cells were subsequently washed with PBS, and packaging cells medium without G418 was added. The conditioned medium containing the viral particles was collected after 24 h, filtered (Schleicher and Schuell, Dassel, Germany, 0.45 µm pore size), and either used immediately or stored frozen at -80°C. Transductions were carried out by exposing OPCs to retroviral particles, 8 µg/ml polybrene, 10 ng/mL FGF-2 and 10 ng/mL PDGF-AA

for 16-18 hrs. The cells were cultured for 24 hrs and then cultured under selection in SATO medium supplemented with FGF-2, PDGF-AA, and 400 µg/mL G418 during 5 days. After selection the cells were cultured in SATO with 0.5 % FCS for 10 days.

VSV infection

VSV strain San Juan A was a kind gift from dr. Peter Rottier (University of Utrecht, The Netherlands). OLGs were washed twice with serum free media pH 6.8 before adding the virus. The virus was incubated with the cells for 1 hrs without CO₂. After this, medium was removed and replaced with fresh culture medium pH 7.4 without serum and incubated at 5-7% CO₂ for 6-8 hrs.

qPCR analysis

Total RNA from cells was isolated using the InviTrap Spin Cell RNA Mini Kit (Strattec, Berlin, Germany). Total RNA (1 µg) was reversed transcribed in the presence of oligo(dT)12-18 and dNTPs (Gibco, Paisley, UK) with superscript II reverse transcriptase (Roche Diagnostics, Mannheim, Germany) according to the manufacturer's instructions. qPCR amplifications were performed on copy DNA using primers specific for rat MBP with exon-II, rat MBP without exon-II and the house-keeping genes HBMS and HPRT1, i.e., 5'-CACATGTACAAGGACTCACAC-3' (forward exon-II-containing MBP), 5'-GAAGAAGTGGACTACTGGGT-3' (reverse exon-II-containing MBP), 5'-ACTTGGCCACAGCAAGTACC-3' (forward exon-II-negative MBP), 5'-TGTGTGAGTCCTTGCCAGAG-3' (reverse exon-II-negative MBP), 5'-CCGAGCCAAGCACCAGGAT-3 (forward HMBS), 5'-CTCCTTCCAGGTGCCTCAGA-3' (reverse HMBS), 5'-GACTTGCTCGAGATGTCA-3' (forward HPRT1), and 5'-ACCACCCTGTTGCTGTAG-3' (reverse HPRT1). The mRNA expression of rat MBP with and without exon-II were measured by real-time qPCR on a StepOnePlus system (Applied Biosystems, Foster City, CA) with Absolute SYBR Green ROX mix according to the following conditions: 15 min at 95°C, followed by 40 cycles of denaturation at 95°C for 15s, annealing at 60°C for 30s and extension at 72°C for 30s, followed by a melting curve stage. The melting curve stage was cycled first 15s at 95°C, then 1 min at 60°C after which the temperature was increased by 0.3°C each 15s to a final temperature of 95°C which was held for 15s. The results were analyzed with StepOne software and normalized to the house-keeping genes HBMS and HPRT1.

Immunocytochemical analysis

Monocultures: For live staining of surface components, a specific binding was blocked with 4% BSA in PBS for 10 min at 4°C, after which cells were incubated with A2B5 (anti-gangliosides, a kind gift of dr. Thijs Lopes-Cardozo) for 30 min at 4°C, washed three times

with ice-cold PBS, and incubated for 25 min at 4°C with appropriate TRITC- or FITC-conjugated antibodies (1:50; Jackson ImmunoResearch Laboratories, Inc., West Grove, PA). Cells were fixed with 4% paraformaldehyde (PFA). For (subsequent) staining of internal antigens, fixed cells were either permeabilized with ice-cold methanol (MBP, hnRNP A2) for 10 min or 0.1% Triton X-100 for 30 min (R-mAb, CNP, PLP, syntaxin 3, syntaxin 4, VAMP3, VSV G). After a 30 min block with 4% BSA, the cells were incubated for 60 min at room temperature (RT) with anti-GalC/sulfatide (R-mAb; a kind gift from Dr. Guus Wolswijk, NIN, Amsterdam, The Netherlands,²¹⁷ anti-CNP (1:100, Sigma), anti-rat syntaxin 3 (1:500, Synaptic Systems, Göttingen, Germany), anti-rat syntaxin 4 (1:500, Synaptic Systems), anti-VAMP3 (1:500, Synaptic Systems), anti-hnRNP A2 (Novus Biologicals, Cambridge, UK), anti-MBP (1:100; rat monoclonal, Serotec, Kinglington, UK), anti-PLP [4C2, 1:10; a kind gift of Dr. Vijay. Kuchroo, Harvard Medical School, Boston, MA²¹⁸ or anti-VSV G (1:100, Sigma). Next, the cells were washed with PBS and incubated for 30 min with appropriate Alexa, TRITC-, or FITC-conjugated secondary antibodies (Molecular Probes, Eugene, OR, and Jackson ImmunoResearch, West Grove, PA, respectively). Nuclei were counterstained with 1 µg/mL DAPI. For double staining, cells were sequentially stained with the different antibodies. Coverslips and slides were mounted in Dako mounting medium and analyzed with a conventional fluorescence microscope (Provis AX70, Olympus, New Hyde Park, NY) or with a confocal laser scan microscope (Leica SP8 AOBS CLSM or Zeiss LSM 780). For differentiation assays, the number of CNP, PLP or MBP of total cells was determined.

Co-cultures: Co-cultures were fixed in 4% PFA and incubated at RT in 0.5% Triton X-100 in 5% normal goat serum (NGS, Vector Laboratories, Burlingame, CA) for 45 min. After washing with PBS, cells were incubated for 2 hrs at RT with anti-MBP (1:250), anti-GFP (1:100 Molecular Probes), anti-PLP (1:50), and anti-NF-H antibodies (1:5000, EnCor Biotechnology Inc, Gainesville, FL) diluted in 2% NGS. Staining was visualized by an incubation for 30 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 (Zeiss LSM 780). To determine the myelination potential for transduced cells, the ability of 50 GFP-positive cells to establish MBP- or PLP-positive internodes per coverslip was established with at least 3 coverslips per condition, and mock-transduced cells set at 100%.

(Co)-immunoprecipitation

Cells were washed and scraped in PBS, and lysed on ice for 30 min in TNE-lysis buffer (50 mM Tris-HCl, 5 mM EDTA, 150 mM NaCl, 1% Triton X-100, and a cocktail of protease inhibitors (Complete Mini, Roche). For immunoprecipitation of integrins, surface proteins were first biotinylated as described¹¹². Protein concentrations were determined by a BioRad DC protein assay (Bio-Rad Laboratories, Hercules, CA) using bovine serum albumin (BSA) as standard. Equal amounts of protein (25 µg) were incubated with 20 µl A/G plus agarose beads (SantaCruz Biotechnology, Santa Cruz, CA) in TNE-lysis buffer with the anti-integrin

$\alpha 6$ antibody (1:100, Millipore, Chemicon, Bedford, MA) overnight head over head at 4°C. Beads were washed four times with IP-wash buffer (TNE-lysis buffer supplemented with 1% NP-40 and 350 mM NaCl), once with PBS, and resuspended in non-reducing SDS-sample buffer. After 5 min at 95°C proteins were separated by SDS-PAGE followed by Western blotting, and detection of (surface) integrin $\alpha 6$ using IR-dye 680-conjugated streptavidin (Li-Cor Biosciences, Lincoln, NE) and IR-detection (see below).

Cells for protein-RNA co-immunoprecipitations were scraped in TNE-lysis-buffer supplemented with RNase inhibitors (New England Biolabs, Ipswich, MA), followed by centrifugation for 15 min at 12000 rpm. Equal amount of protein (40-80 μ g) were incubated overnight at 4°C with precleared A/G plus agarose beads and 4 μ g antibody (syntaxin 4, VAMP3). After washing with IP wash buffer samples were either resuspended in reducing sample buffer for Western Blot analysis or received proteinase K treatment [30 μ g proteinase K (Ambion, Life Technologies) in HNTM buffer (50 mM HEPES, pH 7.5, 150 mM NaCl, 1 mM MgCl₂, and 1% Triton X-100)] at 50°C for 30 min, after which RNA was isolated with TRI Reagent (Sigma) for qPCR analysis.

***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, according to ²¹⁹. Notably, individual probes will bind to other MBP isoforms, however, 30-40 probes should bind for visualization, and given that in OPCs hardly, if at all, probe labelling is observed, visual hybridisation with i.e., golli-MBP can be excluded. Cells were fixed in 4% PFA and opened with ethanol, incubated overnight at 37°C with 1 ng/ μ l probe mix in 10% formamide-containing hybridization buffer and washed with SSC (150 mM NaCl, 15 mM sodium citrate). If co-labeling with antibodies was required, cells were subsequently blocked with BSA and incubated with primary and secondary antibodies as described above. Coverslips were mounted in Dako mounting medium and analyzed with a confocal laser scan microscope (Leica SP8 AOBS CLSM or Zeiss LSM 780).

Western blot analysis

Cells were harvested by scraping in PBS, centrifuged for 7 min at 7000 rpm, followed by lysis of the cell pellets in TNE-lysis buffer. Equal protein amounts (20 μ g) were mixed with SDS reducing sample buffer, heated for 5 min at 95°C or 30 min at 37 °C (PLP) and subjected to SDS-PAGE and Western blotting as described previously ²²⁰. Primary antibodies used were anti-rat syntaxin 3 (1:1000), anti-rat syntaxin 4 (1:1000), anti-VAMP3 (1:3000, Synaptic Systems), anti-MBP (1:100; rat monoclonal, Serotec, Kinglington, UK), anti-PLP (4C2 or 2D2, 1:100), anti-CNP (1:250), anti-integrin $\alpha 6$ (1:500), or anti-actin antibody (1:1000; mouse monoclonal, Sigma). The signals were detected using the Odyssey Infrared Imaging System

(Li-Cor Biosciences, Lincoln, NE) and analyzed using Odyssey V3.0 analysis software. The anti-PLP antibody 4C2 is directed against a non-conformational epitope in the first extracellular loop (PLP 50-69), and recognizes both PLP and its minor splice variant DM20, whereas anti-PLP antibody 2D2 is directed against an intramolecular region that is absent in DM20 (PLP 100-123). Only the band corresponding to PLP is used in the quantitative analysis.

Statistical analysis

Data are expressed as mean \pm standard deviation (SD) and were obtained from at least three independent experiments. Statistical analysis was performed using the one sample t-test when compared relative to control that was set to 100% in each independent experiment. When absolute values of more than two means were compared, statistical significance was calculated by a one way ANOVA, followed by a Tukey's post-test. In all cases a p value of $p < 0.05$ was considered significant.

RESULTS

Syntaxins 3 and 4 differentially localize to cell body and myelin sheet, respectively, in oligodendrocytes

Upon development, OLGs undergo a carefully defined process of maturation, during which different morphological features can be discerned. Thus, the cells differentiate from a bipolar progenitor cell (OPC) to a cell with more and branched primary processes (imOLG) and eventually to one with elaborate laminar sheets (mOLG) (Fig. 1A) ^{221,222}. Not only is this development accompanied by the biosynthesis of myelin-specific proteins, including CNP, MBP and PLP (Fig. 1B), also different surface membrane domains are generated and maintained. Thus, in addition to the cell body plasma membrane, constituting the main boundary domain during early development (OPC, Fig.1A), an elaborate myelin-like membrane domain (sheet) is formed upon full differentiation (mOLG, Fig. 1E, arrow). Given previous observations that the plasma membrane and the myelin sheet are served by cognate apical and basolateral trafficking ^{114,115}, respectively, and since syntaxins 3 and 4 are known to be localized at and near distinct membrane surfaces in polarized cells ²⁰¹, we wondered whether these syntaxins also distributed differently in OLGs, and whether they could similarly play a prominent role in the sorting and trafficking events involved in the assembly of myelin membranes. We therefore first determined the protein expression pattern of both syntaxins as a function of OLG development. Total lysates obtained at different developmental stages of primary OLGs were analyzed by Western blotting. As shown in Figure 1 (B, C), the expression level of syntaxin 3 remained remarkably constant during rat OLG development. Interestingly and in marked contrast, the expression of syntaxin 4 was substantially upregulated during developmental progression (Fig. 1B, D) and, relative to its expression in OPCs, increased more than four-fold under conditions of avid myelin membrane biogenesis (mOLGs). From these data it is tempting to suggest that syntaxin 4 might be particularly involved in myelin sheet-directed transport, whereas syntaxin 3 would largely act in docking and fusion of transport vesicles directed towards the cell body plasma membrane. To investigate this possibility, the localization of syntaxins 3 and 4 at the different developmental stages was visualized by immunofluorescence, using antibodies directed against gangliosides (A2B5), the galactosphingolipids GalC and sulfatide (R-mAb), and MBP, as markers for OPCs, immature and mature OLGs, respectively. In all developmental stages, syntaxin 3 largely localizes to the perinuclear region along with a more punctuate distribution throughout the cytoplasm of the cell body, presumably reflecting its association with vesicular structures (Fig. 1E, left panel). In fully differentiated MBP-positive cells (mOLGs), no significant localization of syntaxin 3 at the myelin sheet could be observed (Fig. 1E, left panel, arrow), and the protein mainly localized to the cell body and, occasionally, at primary processes. In A2B5-positive OPCs, syntaxin 4, was located in intracellular vesicles and at the plasma membrane of the cell body. At later stages of development, syntaxin 4 was directed towards the membrane of the processes, and in marked contrast to the localization of syntaxin 3, abundantly localized within the myelin sheet, displaying a more prominent membrane association than seen for

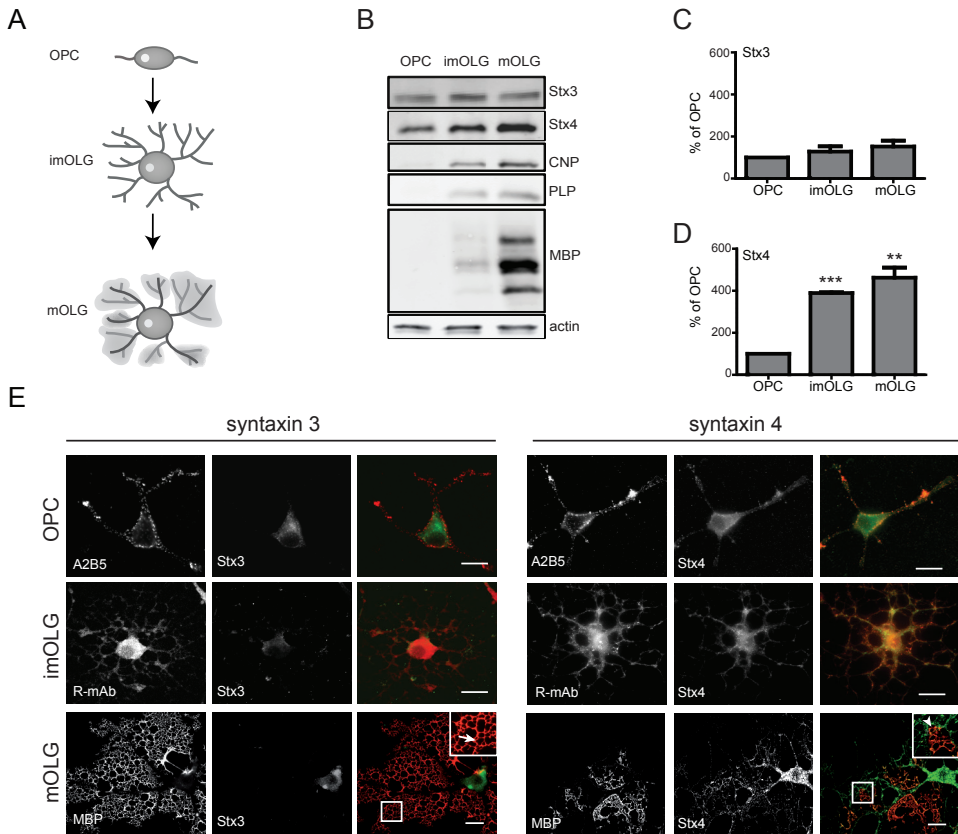


Figure 1. Upregulation of syntaxin 4 during rat oligodendrocyte development

A) Schematic overview of oligodendrocyte development and differentiation as reflected by changes in morphology for oligodendrocyte progenitor cells (OPCs), via immature oligodendrocytes (imOLG) to mature and fully differentiated cells (mOLG). Mature cultured OLG form myelin-like membranes, i.e., sheets, the *in vitro* equivalent of (non-compact) myelin sheaths *in vivo*. **B-D)** Cell lysates of OPCs, imOLGs and mOLGs were analyzed for protein expression of syntaxin 3 (Stx3), syntaxin 4 (Stx4), CNP, PLP (2D2) and MBP. Actin served as a loading control. Quantification of protein levels of syntaxin 3 is shown in C) and of syntaxin 4 in D). Expression, as a ratio of actin, was quantified relative to that of OPCs (set at 100%). Bars depict mean + SD. Data were obtained from four independent experiments. Statistical significance between OPC and the other developmental stages is shown (** $p < 0.01$, *** $p < 0.001$, one sample t-test). Note that with increase of (im)mature OLG markers CNP, PLP and MBP, the expression of syntaxin 4, but not syntaxin 3, is upregulated. **E)** Localization of syntaxins 3 and 4 (green) in A2B5-positive OPCs, R-mAb positive imOLGs and MBP-positive mOLGs. Insets show higher power magnifications. Note that in mOLGs syntaxin 4 is more localized towards myelin sheets (inset, arrow), whereas syntaxin 3 is more retained to the cell body. Scale bars are 10 μm .

syntaxin 3 (Fig. 1E, right panel, arrowhead). Thus, these data reflect a preferential polarized distribution of the syntaxins in cultured rat OLGs, syntaxin 3 primarily localizing to the cell body, whereas syntaxin 4 shows a preferential association towards the myelin sheet. This apparent polarized distribution could be indicative of potential distinct roles of these syntaxins in myelin biogenesis. Given the upregulation of syntaxin 4 during development (Fig. 1B, D), and its localization at the myelin membrane (Fig. 1E, right panel), we investigated in particular the role of this syntaxin in the biogenesis of myelin membranes, focusing on myelin-directed transport of the major proteins MBP and PLP.

Downregulation and overexpression of syntaxin 4, but not syntaxin 3, precludes the expression of MBP

To assess a functional role for either syntaxin in myelin biogenesis, we downregulated their expression by transducing OPCs using a lentiviral construct that concomitantly expresses shRNA directed against syntaxin 3 or 4 and GFP. Western blot analysis of total cell lysates of mature OLGs revealed that by this approach, which resulted in a transduction efficiency of 60-80%, the levels of syntaxin 3 and 4 were reduced by approx. 50 and 60% respectively (Fig. 2A, B). In addition, upon downregulation of syntaxin 4, it was noted that the levels of syntaxin 3 expression were consistently reduced by approx. 20%. Upon downregulation of either syntaxin 3 or syntaxin 4, the level of expression of the myelin specific proteins 2' 3' -cyclic nucleotide phosphodiesterase (CNP) and PLP in mature OLGs were virtually unaffected (Fig. 2A, C). Intriguingly, downregulation of syntaxin 4, but not syntaxin 3, caused a virtual abolishment of MBP expression (Fig. 2A, C). To verify whether downregulation of either syntaxin affected the intracellular distribution of the investigated proteins, transduced, i.e., GFP-positive cells, were examined for CNP, MBP and PLP expression and localization. Consistent with the Western blot analysis, MBP expression was virtually absent in syntaxin 4-downregulated cells (Fig. 2D, top panel), whereas in syntaxin 3-downregulated cells the distribution of MBP was very similar to that observed in mock-transduced cells. Syntaxin 4 downregulation did not significantly affect the number of CNP and PLP-expressing cells (Fig. 2E), when compared to mock (vector-only)-transduced cells (Fig. 2D, E). However, at these conditions PLP, although still residing in vesicular structures, was more localized to the processes and myelin sheets, likely due to the lack of MBP expression³². In marked contrast, upon downregulation of syntaxin 3, PLP appears largely retained in the cell body (Fig. 2D). However, syntaxin 3 downregulation did not affect the number of cells that express CNP, MBP or PLP in the transduced OLGs (Fig. 2E).

To obtain further support for the remarkable observation of a syntaxin 4-dependent modulation of MBP expression, the effect of overexpression of syntaxin 4 was examined as well. As previously reported, overexpression of syntaxin leads to assembly of non-functional SNARE complexes, thereby mimicking dominant-negative features^{176,180}. Thus syntaxins 3 and 4 were overexpressed in OPCs using a retroviral expression system, followed by selection of the transduced cells. As shown in Figure 3A, the localization of overexpressed syntaxin 3 and 4 resembled that of the respective endogenous syntaxins (cf. Fig. 1E), syntaxin 3 localizing

largely to the cell body, whereas syntaxin 4 was prominently present in the processes and in the sheets. In all cases, the morphology of the cells and/or the appearance of myelin-like membranes were indistinguishable from those of mock-transduced cells. At a roughly 7 fold overexpression of syntaxin 3 and 4 (Fig. 3C, D respectively), no differences were observed between the overexpressed and mock-transduced cells in terms of the number of cells that expressed CNP and PLP (Fig. 3E). Also, irrespective of the overexpressed syntaxin species, the expression levels of CNP or PLP were indistinguishable (Fig. 3F). However, as observed upon syntaxin downregulation, overexpression of syntaxin 4, but not syntaxin 3, resulted

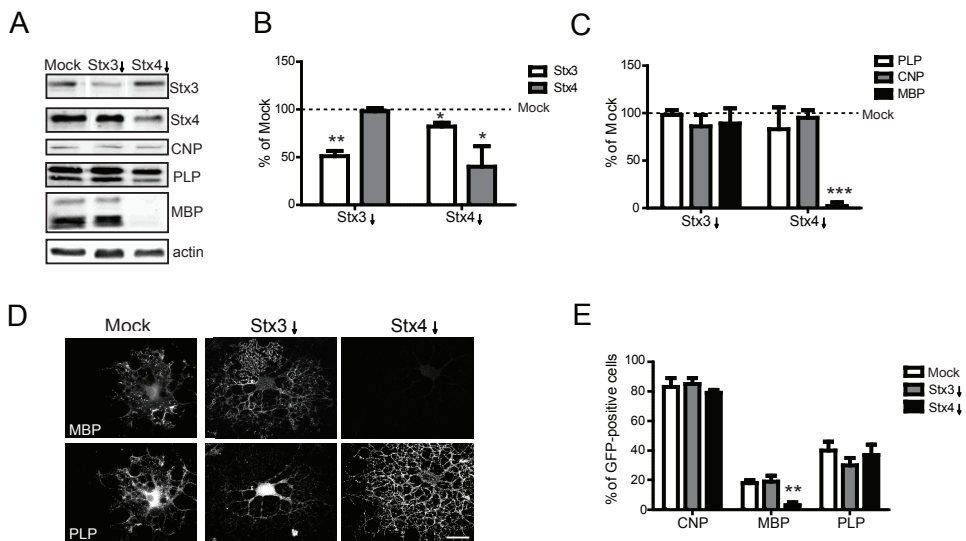


Figure 2. Downregulation of syntaxin 4, but not syntaxin 3, decreases MBP protein levels in oligodendrocytes

Primary rat oligodendrocyte progenitor cells (OPCs) were transduced with lentiviruses that express vector-only (Mock) or shRNA against either syntaxin 3 (Stx3↓) or 4 (Stx4↓). **A-C**) After 7 days, cell lysates were analyzed for protein levels of Stx3, Stx4, CNP, MBP, and PLP (4C2). Actin served as a loading control. Quantification of protein levels of (A) is shown in (B, syntaxins) and (C, myelin-specific proteins). Expression, as a ratio of actin, was quantified relative to that of mock (set at 100%, horizontal line). Bars depict mean + SD. Data were obtained from three (B) and five (C) independent experiments. Statistical differences with mock-transduced cells are shown (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, one sample t-test). Note that syntaxin 4, but not syntaxin 3, downregulation decreases MBP protein expression. **D, E**) After 7 days, cells were fixed and permeabilized to perform double immunocytochemistry for the indicated proteins. Representative images of three independent experiments are shown (D). Scale bar is 10 μ m. Note that syntaxin 3-downregulated cells generated MBP-positive sheets, whereas PLP is more retained in the cell body as compared to mock-transduced cells. Syntaxin 4 silenced cells show hardly, if at all MBP staining, whereas PLP is present deep into the processes. The percentage of cells positive for CNP, MBP or PLP of total GFP-positive, i.e., transduced cells, are shown in (E). At least 500 cells per experiment were analyzed in three independent experiments. Bars depict mean + SD. Statistical differences with mock-transduced cells are indicated (** $p < 0.01$, one-way ANOVA with Tukey's post-test). Note that in syntaxin 4-downregulated oligodendrocytes MBP-positive cells were hardly observed.

in the virtual absence of MBP expression (Fig. 3F). Similarly, upon visual examination, the number of MBP-positive cells was dramatically reduced, if present at all, upon syntaxin 4 overexpression (Fig. 3E). Hence, both downregulation and overexpression of syntaxin 4, but not syntaxin 3, precluded MBP protein synthesis, but not that of the myelin-specific proteins PLP or CNP.

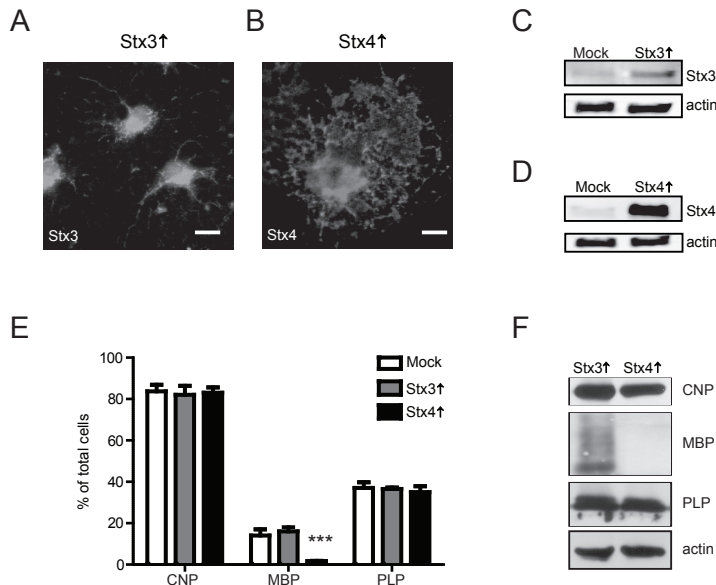


Figure 3. Overexpression of syntaxin 4, but not syntaxin 3, decreases MBP levels in oligodendrocytes

Primary rat oligodendrocyte progenitor cells (OPCs) were transduced with retroviruses that express vector-only (Mock), syntaxin 3 (Stx3 \uparrow) or 4 (Stx4 \uparrow), and after selection, analyzed 10 days after initiating differentiation. **A**) Localization of syntaxin 3 in syntaxin 3-overexpressing mature oligodendrocytes (OLG). Note that upon its overexpression, syntaxin 3, as endogenous syntaxin 3 (cf. Fig. 1E), does not localize to myelin sheets. **B**) Localization of syntaxin 4 in syntaxin 4-overexpressing mature OLGs. Note that in overexpressing cells, syntaxin 4 localized to myelin-like membranes, similarly as observed for the distribution of endogenous syntaxin 4 (cf. Fig. 1E). Scale bar is 10 μ m. Representative pictures of three independent experiments are shown in (A) and (B). **C**) Western blots of syntaxin 3 expression in mock (vector-only)-infected and syntaxin 3-overexpressing OLGs. Actin served as a loading control. **D**) Western blots of syntaxin 4 expression in mock (vector-only)-infected and syntaxin 4-overexpressing OLGs. Actin served as a loading control. **E**) Cells were fixed and permeabilized to perform immunocytochemistry for CNP, MBP and PLP. The percentage of cells positive for CNP, MBP or PLP in the overexpressing cells were determined. At least 500 cells per experiment were analyzed in three independent experiments. Bars depict mean \pm SD. Statistical differences with mock-transduced cells are indicated (*** $p < 0.001$, one-way ANOVA with Tukey's post-test). Note that in syntaxin 4-overexpressing OLGs MBP-positive cells were hardly observed. **F**) Cell homogenates were analyzed for protein levels of CNP, MBP, and PLP (2D2). Actin served as a loading control. Note the virtual absence of MBP expression in syntaxin 4-overexpressing OLGs.

Downregulation of syntaxin 4 prevents the expression of MBP, but not PLP, at internodes in myelinating co-cultures

To better appreciate the relevance of these observations, which were recorded in enriched OLG mono-cultures, we verified these data in mixed myelinating OLG-dorsal root ganglion neuron (DRGN) cultures. Moreover, in this manner some insight would be obtained into the functional consequences of myelination in the absence of MBP. Thus, syntaxin 3 and 4 were downregulated in OPCs prior to their seeding onto DRGNs. Immunocytochemical analysis of 14-day old co-cultures showed that also in the presence of neurons, MBP, but not PLP, is virtually absent from myelin segments in syntaxin 4 downregulated cells (Fig. 4A, B). Thus, neuronal-derived signals were not able to overcome syntaxin 4-mediated downregulation of MBP mRNA transcription. Furthermore, the typical morphology of the myelinated membranes were seriously compromised in syntaxin 4-downregulated cells. In syntaxin 3-downregulated cultures, cells with MBP-positive internodes were readily observed and, in terms of cell number, were indistinguishable from those seen in mock-transduced cells

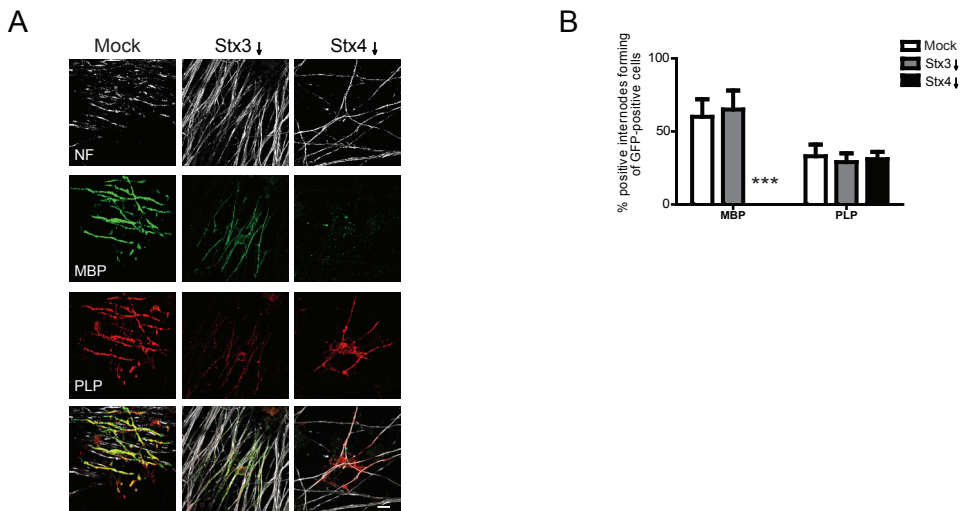


Figure 4. Downregulation of syntaxin 4, but not syntaxin 3, decreases MBP-positive internodes in oligodendrocyte-DRG neuron cocultures

A,B) Transduced OPCs were co-cultured with dorsal root ganglion neurons (DRGNs) for 14 days, after which the cultures were subjected to triple immunocytochemistry for neurofilament-H (NF, white), PLP (red) and MBP (green). Representative images of three independent experiments are shown (A). Scale bar is 10 μ m. The percentage of GFP-positive cells that produce PLP- or MBP-positive myelin segments are shown in (B). Bars depict mean + SD. Data were obtained from three independent experiments. Statistical differences with mock-transduced cells are indicated (***) $p < 0.001$, one-way ANOVA with Tukey's post-test). Note that also in oligodendrocyte-DRGN co-cultures hardly, if at all, MBP-positive myelin segments are observed upon syntaxin 4, but not syntaxin 3, downregulation.

(Fig. 4A, B). In this case the intensity of PLP in the myelin segments was clearly reduced, along with prominent expression of PLP in the cell body, although the cellular morphology and ability to form myelin membranes was largely retained.

Downregulation of syntaxin 4 does not affect vesicular delivery of several myelin sheet-directed proteins

The data presented thus far suggest that downregulation of syntaxin 4 interferes with MBP expression without affecting expression and/or transport of relevant myelin-specific proteins like PLP and CNP, as investigated in this work. To determine whether vesicular transport of other myelin sheet-directed proteins was perturbed, we next analyzed the localization of VSV G, a viral model protein for myelin-sheet directed traffic^{19,114,115,120}. Also the transport of VSV G was seemingly unaffected upon downregulation of syntaxin 4, as VSV G is transported and localized to myelin-like membranes in syntaxin 4-downregulated cells, i.e., in the absence of MBP, similar to mock-transduced cells (Fig. 5A, arrow). To verify therefore whether transport of compounds specifically relevant to the regulation of MBP expression might be perturbed, we investigated if trafficking of integrin $\alpha 6$, which localizes to the surface of myelin membranes in mature OLGs²²³ and is involved in MBP expression¹⁷, relies on syntaxin 4.

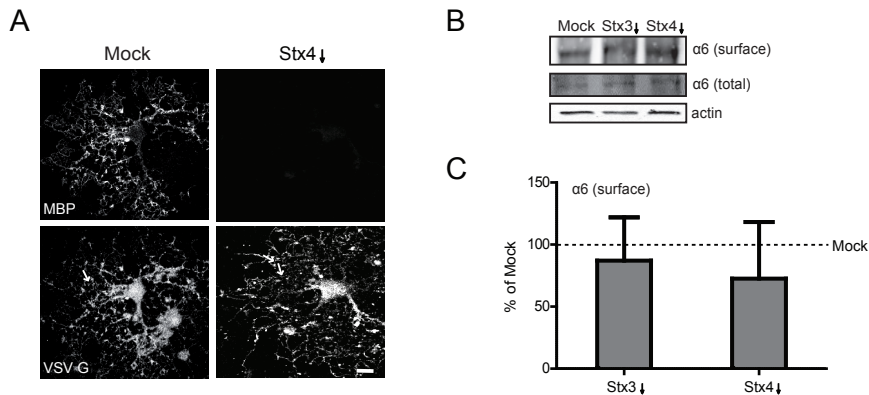


Figure 5. Downregulation of syntaxin 4 does not affect vesicular delivery of myelin sheet-directed protein

A) Primary rat oligodendrocyte progenitor cells (OPCs) were transduced with lentiviruses that express vector-only (Mock) or shRNA against syntaxin 4 (Stx4↓). After 7 days, cells were infected with VSV, and after 6 hrs labeled for VSV G. Note that vesicular transport is not impeded upon syntaxin 4 downregulation, as VSV G still localizes to the myelin sheet (arrow). **B, C)** OPCs were transduced with lentiviruses that express vector-only (Mock) or shRNA against syntaxin 3 (Stx3↓) or 4 (Stx4↓). After 7 days, cells were surface biotinylated, followed by immunoprecipitation for integrin $\alpha 6$. Integrin $\alpha 6$ and actin in total cell lysates served as input control. Integrin surface expression was quantified relative to that of mock-transduced cells in C (set at 100%, horizontal line, $p > 0,05$ (non-significant, one sample t-test). Bars depict mean + SD. Data were obtained from three independent experiments.

Thus, by means of surface biotinylation and immunoprecipitation, we quantified the pools of integrin $\alpha 6$ present on the surface of OLGs in mock and syntaxin 4-downregulated cells. The data as presented in Figure 5B and C demonstrate that irrespective of the presence of syntaxin 4, the level of surface association of integrin $\alpha 6$ remained unaltered and its total expression is similar at all conditions (Fig. 5B). Moreover, these data also emphasize, as revealed by quantitation of the integrin $\alpha 6$ surface-pool and localization of VSV G, that effective downregulation of syntaxin 4 has little if any effect on the vesicular delivery of these proteins to the myelin sheets.

To obtain further insight into the underlying mechanism of the syntaxin 4 dependent failure of MBP expression, we therefore took into account the possibility that MBP mRNA granule transport^{12,224} might rely on the SNARE machinery, and that sheet-localized syntaxin 4 fulfils a crucial role in proper granule docking and concomitant localized MBP expression.

The SNARE machinery is not involved in mRNA granule transport

Interacting binding partners of syntaxin 4 in vesicular transport are v-SNAREs, known as vesicle-associated membrane proteins (VAMPs). In OLGs, the t-SNARE syntaxin 4 is recognized by VAMP3^{8,39}. To assess, therefore, whether VAMP3 might be involved in facilitating the expression of MBP, we next examined the effect of VAMP3 downregulation on MBP expression. As shown in Figure 6A and B, an approx. 60% downregulation of VAMP3 resulted in a reduction in MBP expression levels of approx. 30%, as compared to those obtained in mock-transduced cells. A slight increase in the expression of syntaxin 4 is observed upon downregulation of VAMP3 which may add to the reduction of MBP expression. The expression levels of CNP and PLP were unaffected. These findings thus suggest that the SNARE machinery could be at least partly involved in regulating MBP expression. However, whether this reduced expression is related to a defect in mRNA transport and/or docking is not apparent from these data. We therefore determined the extent to which VAMP3 and MBP mRNA were co-localizing in the cells, as examined by fluorescence co-localization. To visualize MBP mRNA, 48 short fluorescent probes were employed that specifically bind to the 14 kDa MBP, the major MBP isoform present in rodent myelin^{204,206}, and which allows for single MBP mRNA detection²²⁵. As shown in Figure 6C, VAMP3, although clearly visible as punctate green dots, presumably representing VAMP3-labelled transport vesicles, does not significantly co-localize with MBP mRNA (red). To obtain further support for this notion, co-immunoprecipitation studies were carried out which neither revealed any association between MBP mRNA and VAMP3 (data not shown). Finally, we visualized the fate of mRNA granules as such in OLGs by immunocytochemical analysis, employing antibodies against hnRNP A2, a prominent constituent of mRNA granules^{18,184,186}. As shown in Figure 6D, hnRNP A2 was localized deeply into the processes of both mock-transduced cells and syntaxin 4-, syntaxin 3- and VAMP3-downregulated cells. Also, irrespective of SNARE downregulation, the cellular distribution of granules, as reflected by the hnRNP A2 marker, is indistinguishable from their fate in mock-transduced

cells. These data thus suggest that hnRNP A2-containing granules are seemingly properly assembled in the downregulated cells, and can be subsequently transported into the processes of OLGs, even in cells with little if any syntaxin 4. Together, these data indicate that the lack of MBP expression is not related to defects in granule assembly or transport *per se*. Rather, the findings obtained so far strongly favour the hypothesis that downregulation of the syntaxin 4 machinery leads to a transcriptional suppression of MBP mRNA, as occurs most efficiently by downregulation of the t-SNARE itself, and less so by that of the v-SNARE, VAMP3. To obtain direct support for this hypothesis the level and localization of MBP mRNA expression was therefore investigated in VAMP3, syntaxin 3- and syntaxin 4-downregulated cells.

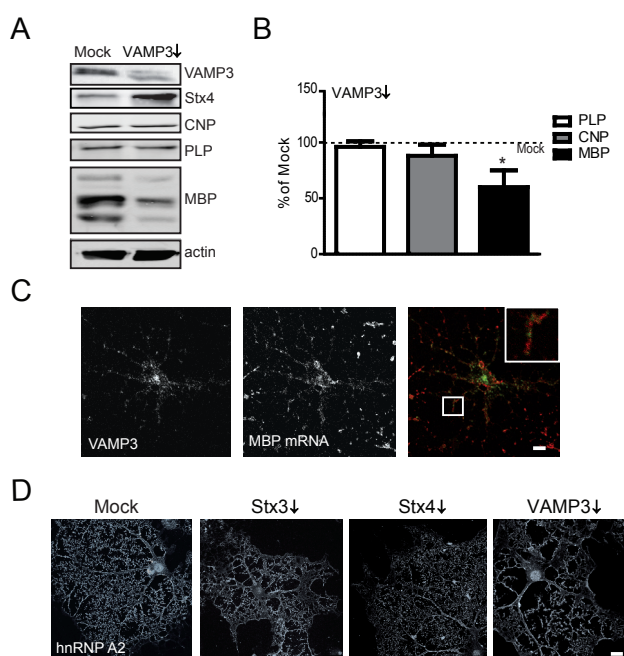


Figure 6. The SNARE machinery is not involved in MBP mRNA granule transport

A, B Primary rat oligodendrocyte progenitor cells (OPCs) were transduced with lentiviruses that express vector-only (Mock) or shRNA against VAMP3 (VAMP3↓), and analyzed 7 days after transduction for protein levels of VAMP3, CNP, PLP (2D2) and MBP. Actin served as a loading control. Quantification of protein levels of **(A)** is shown in **(B)**. Expression, as a ratio of actin, was quantified relative to that of mock (set at 100%, horizontal line). Bars depict mean + SD. Data were obtained from three independent experiments. Statistical differences with Mock-transduced cells are indicated (* $p < 0.05$, one sample t-test). Note that VAMP3 downregulation decreases MBP protein expression. **C** Non-transduced mature oligodendrocytes were double-labelled for VAMP3 and MBP mRNA. Note that VAMP3 hardly if at all colocalize with MBP mRNA. Scale bar is 10 μ m. **D** OPCs were transduced with lentiviruses that express vector-only (Mock) or shRNA against VAMP3 (VAMP3↓), syntaxin 3 (Stx3↓) or 4 (Stx4↓), and labelled 7 days after transduction for hnRNP A2, a prominent constituent of mRNA granules.

The syntaxin 4 machinery regulates MBP mRNA expression

To examine the presence and distribution of MBP mRNA in syntaxin 3 and syntaxin 4 as well as in VAMP3 downregulated OLGs, RNA *in situ* hybridisation experiments were carried out. As shown in Figure 7A, in mock-transduced cells, MBP mRNA is present in the cell body and penetrates deeply into the primary and secondary processes. Interestingly, upon downregulation of syntaxin 4, but not syntaxin 3, hardly any MBP mRNA signal, if at all, can be detected. In VAMP3-downregulated cells, a seemingly reduced level of MBP mRNA transcripts were detected only in the processes and cell body (Fig. 7A), consistent with a somewhat diminished but not completely abolished level of MBP expression in these cells (Fig. 6A, B). Additional support for a lack of MBP mRNA transcription upon syntaxin 4 downregulation was obtained by real time qPCR analysis (Fig. 7B). Specifically, transcriptional regulation of MBP mRNA upon downregulation of syntaxin 4 was apparent for transcripts of exon-II-negative MBP isoforms, which are transported to and expressed at the myelin membrane, and for transcripts of exon-II-containing MBP isoforms, which mainly reside in the cytoplasm and nucleus^{226,227}. Accordingly, these data indicate that the syntaxin 4-mediated transcriptional suppression of MBP mRNA is a general effect on MBP mRNA transcription, and does not appear to be restricted to MBP isoforms, exclusively expressed in the myelin sheet.

If a syntaxin 4-dependent mechanism is required for allowing transcriptional expression of MBP to proceed, we would predict that downregulation of syntaxin 4 at a later developmental state, i.e., after the initiation of MBP transcription, should not affect MBP (protein) expression. To examine this, immature OLGs were lentivirally transduced with shRNA against syntaxin 4.

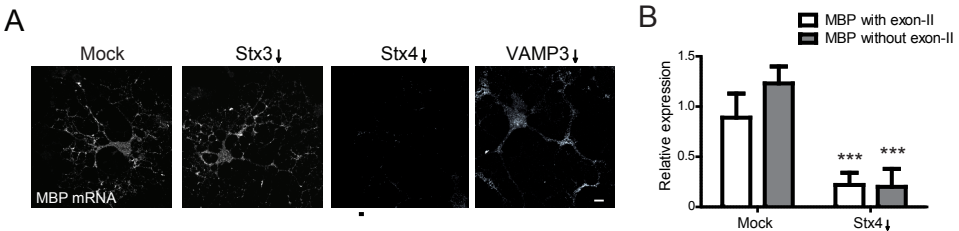


Figure 7. Downregulation of syntaxin 4, but not syntaxin 3, decreases MBP mRNA levels in oligodendrocytes

A) Primary rat oligodendrocyte progenitor cells (OPCs) were transduced with lentiviruses that express vector-only (Mock) or shRNA against VAMP3 (VAMP3↓), syntaxin 3 (Stx3↓) or 4 (Stx4↓), and analyzed 7 days after transduction cells were labelled for MBP mRNA. Scale bar is 10 μ m. Note that MBP mRNA is virtually absent upon syntaxin 4, but not VAMP3 downregulation. **B)** OPCs were transduced with lentiviruses that express vector-only (Mock) or shRNA against syntaxin 4 (Stx4↓), selected, and 7 days after differentiation 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. Data were obtained from three independent experiments. Statistical differences with mock-transduced cells are shown (***) $p < 0.001$, one sample t-test). Note that downregulation of syntaxin 4 results in significant lower levels of both exon-II-positive and -negative MBP isoforms.

Indeed, downregulation of syntaxin 4 from the imOLG stage onwards does not affect the level of MBP (protein) expression (Fig. 8A, B), when compared to the level obtained in mock-transduced cells (Fig. 8A, B). Also, the localization of MBP protein and MBP mRNA in

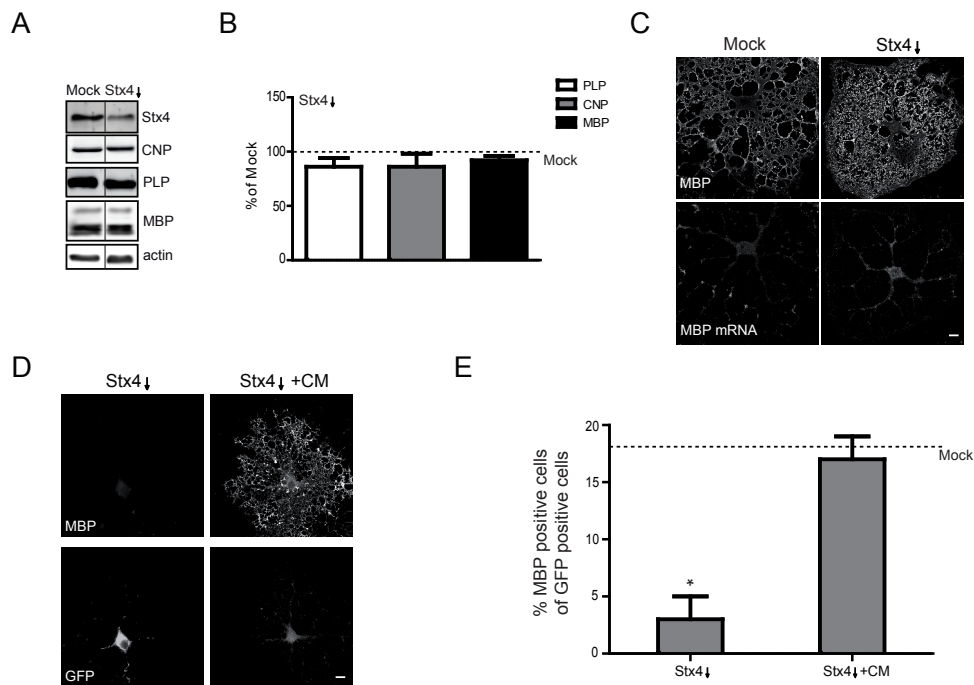


Figure 8. Conditioned medium of developing OPCs re-established MBP expression in syntaxin 4-downregulated cells

A, B) Primary immature rat oligodendrocytes (imOLGs) were transduced with lentiviruses that express vector-only (Mock) or shRNA against syntaxin 4 (Stx4↓). After 7 days, cell lysates were analyzed for protein levels of Stx4, CNP, MBP, and PLP (2D2). Actin served as a loading control. The cells lysates of syntaxin 4-downregulated and mock-transduced cells are on the same blot. Quantification of protein levels of **(A)** is shown in **(B)**. Expression, as a ratio of actin, was quantified relative to that of ctrl (set at 100%, horizontal line). Bars depict mean + SD. Data were obtained from at least three independent experiments. Statistical differences with mock-transduced cells are shown (* $p < 0.05$, one sample t-test). Note that syntaxin 4 downregulation from imOLGs onwards hardly affects MBP protein expression. **C**) imOLGs were transduced as in **(A, B)**. After 7 days, cells were labeled for MBP protein and MBP mRNA. Representative images of three independent experiments are shown. Scale bar is 10 μ m. Note that the appearance of MBP protein and mRNA in syntaxin 4 downregulated cells were indistinguishable from those of mock-transduced cells. **(D, E)** Primary rat oligodendrocyte progenitor cells (OPCs) were transduced with lentiviruses that express vector-only (Mock) or syntaxin 4 shRNA (Stx4↓). Upon differentiation cells were treated with control medium (ctrl, Mock and Stx4↓) or conditioned medium of developing OPCs (CM, Stx4↓). After 7 days, cells were labelled for MBP protein (red). Representative images of three independent experiments are shown **(D)**. Scale bar is 10 μ m. The percentage of cells positive for MBP of total GFP-positive, i.e., transduced cells, are shown in **(E)**. Bars depict mean + SD. Data were obtained from three independent experiments. Statistical differences with mock-transduced cells are indicated (* $p < 0.05$, one-way ANOVA with Tukey's post-test). Note that conditioned medium of developing OPCs re-established MBP expression in syntaxin 4-downregulated cells.

mock-transduced and syntaxin 4-downregulated cells appear to be indistinguishable, i.e., both MBP protein and mRNA are present and localize deeply into the processes (Fig. 8C). Thus, a syntaxin 4-dependent mechanism is essential for the onset of MBP mRNA transcription. Remarkably, careful examination of the transduced cultures (60-80% efficiency) revealed that MBP was reduced in all cells, i.e., in both transduced and non-transduced cells (Fig. 2A). This observation could thus point towards a potential role of (a) medium-derived factor(s), the presence of which depends on functional active syntaxin 4, that drives MBP mRNA transcription. To obtain experimental support for this possibility, syntaxin 4-downregulated OPCs were differentiated in the presence of conditioned medium derived from developing OLGs, i.e., differentiated from OPCs to immature OLGs, and analyzed after 7 days by immunocytochemistry for MBP expression. Strikingly, in syntaxin 4-downregulated cells, i.e. GFP-positive cells, treated with conditioned medium, MBP protein expression was re-established up to the level of mock-transduced cells (Fig. 8D, E). Thus these findings would support the notion that the initiation of the biosynthesis of MBP mRNA relies on a syntaxin 4-dependent mechanism, which likely involves activation of an autocrine signalling pathway.

DISCUSSION

SNARE proteins, including syntaxins, are intimately involved in docking and fusion of vesicles, mediating intracellular protein transport, and their ubiquitous presence and distinct identities warrants specificity in vesicle-mediated delivery^{119,197,198}. The present study demonstrates that the t-SNAREs syntaxin 3 and 4 are distributed in a polarized fashion in OLGs, in agreement with similar observations reported for more common polarized cells, like epithelial cells^{176–178,200–202}. Moreover, the localization of syntaxin 3 in the cell body and near the plasma membrane on the one hand, and that of syntaxin 4 in the myelin sheet on the other, is consistent with the apical- and basolateral-like nature, respectively, of these regions in rat OLGs, as previously established^{9,29,114,115}. Interestingly, our data also reveal that functional expression of syntaxin 4, and to a lesser extent that of its binding partner, VAMP3, appears crucial for MBP expression at the transcriptional level, but not for MBP mRNA trafficking to the myelin sheet. In fact, our data suggest a role of a syntaxin 4-dependent, autocrine signalling mechanism that regulates MBP mRNA transcription.

Given its role in membrane docking at (basolateral) target domains and its primary localization towards the myelin sheets, we would predict that syntaxin 4 is involved in polarized transport of myelin-sheet directed proteins. Remarkably, its downregulation effectively repressed MBP mRNA transcription. Although a causal relationship between the vesicular transport machinery and mRNA transport and localization has been described^{208,209,228}, our data indicated that neither granule assembly nor its cellular distribution, were affected by syntaxin 4 downregulation. Alternatively, a likely explanation for our findings would be to suggest failure of syntaxin 4-mediated sheet-directed delivery of (a) molecular factor(s), regulating MBP mRNA transcription. However, quite unexpectedly, effective downregulation of syntaxin 4 did not result in significant downregulation of vesicular transport of the myelin-specific protein PLP, the viral model protein VSV G or integrin $\alpha 6$, known to regulate MBP mRNA expression¹⁷. Yet, we cannot exclude that in this particular case sheet-directed transport, mediated by the SNARE machinery, might have exploited alternatives for syntaxin 4, e.g., syntaxin 2, which is present in mature OLGs^{39,179} in a non-polarized manner (our unpublished observations), or for the v-SNARE, VAMP3, e.g., VAMP2^{39,179} or VAMP7, which has been implicated in PLP trafficking⁸. If so, it should also be emphasized that ‘t-SNARE substitution’ does not apply to the apical machinery, driven by syntaxin 3, as in this case its downregulation did effectively preclude PLP trafficking to the plasma membrane of the cell body, which precedes subsequent transport to the myelin sheet^{9,11,25,136,229}. Thus, the specificity of the effect of syntaxin 4 is emphasized by similar observations of a reduction of MBP expression upon downregulation of its v-SNARE, VAMP3, the absence of an effect of syntaxin 3, and the apparent inability to potentially maintain MBP mRNA transcription via a syntaxin 2-mediated pathway.

A direct interaction of the syntaxin 4/VAMP3 SNARE machinery with MBP mRNA containing granules in OLGs could be excluded. Neither could the present observations be

explained by degradation of MBP mRNA, or, in conjunction with that, of MBP. Indeed, downregulation of syntaxin 4 from the immature OLG stage onwards does not lower the amount of MBP, nor were changes in MBP protein levels apparent in the presence of the proteasomal inhibitor ALNN (unpublished observations). In fact, the location of syntaxin 4 near the myelin sheet would *a priori* exclude its direct role as a transcriptional activator. In this context, transcription factors such as myelin gene regulatory factor (MRF), required for expression of myelin genes and CNS myelination, are likely also not the target of syntaxin 4, as they usually facilitate the expression of a group of myelination-related genes, and do not specifically induce MBP expression as such ²³⁰. Furthermore, MRF is also required for the maintenance of mature OLGs and myelin ²³¹, whereas proper functioning of syntaxin 4 is required at the onset of MBP mRNA transcription, its downregulation from the immature OLG stage being without effect on MBP expression. More likely, the absence of MBP as a result of syntaxin 4 downregulation, might reflect the inability of OPCs to secrete (a) factor(s) which is/are apparently necessary to initiate MBP mRNA transcription, i.e., based upon an autocrine signalling mechanism. Indeed, conditioned medium of developing OLGs, but not neuronal-derived signals, restored MBP protein expression in syntaxin 4-downregulated cells. Given that MBP is essential for the formation of functional myelin ^{204,232,233}, it will be important to clarify the identity of this/these medium constituent(s) and its/their underlying mechanism in MBP mRNA transcription during development in order to address early (re) myelination defects.

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