Multifaceted effects of oligodendroglial exosomes on neurons: impact on neuronal firing rate, signal transduction and gene regulation

Dominik Fröhlich1,†, Wen Ping Kuo1,2,†, Carsten Frühbeis1, Jyh-Jang Sun3,6, Christoph M. Zehendner2,7, Heiko J. Luhmann2,3, Sheena Pinto4, Joern Toedling5, Jacqueline Trotter1,2 and Eva-Maria Krämer-Albers1,2

1Molecular Cell Biology, and 2Focus Programme Translational Neuroscience, University of Mainz, 55128 Mainz, Germany
3Institute of Physiology, University Medical Center, 55128 Mainz, Germany
4Division of Developmental Immunology, DKFZ Heidelberg, 69120 Heidelberg, Germany
5Institute of Molecular Biology gGmbH, 55128 Mainz, Germany
6Neuro-Electronics Research Flanders, 3001 Leuven, Belgium
7ZIM III, Department of Cardiology, Goethe University Frankfurt, 60389 Frankfurt, Germany

Exosomes are small membranous vesicles of endocytic origin that are released by almost every cell type. They exert versatile functions in intercellular communication important for many physiological and pathological processes. Recently, exosomes attracted interest with regard to their role in cell–cell communication in the nervous system. We have shown that exosomes released from oligodendrocytes upon stimulation with the neurotransmitter glutamate are internalized by neurons and enhance the neuronal stress tolerance. Here, we demonstrate that oligodendroglial exosomes also promote neuronal survival during oxygen–glucose deprivation, a model of cerebral ischaemia. We show the transfer from oligodendrocytes to neurons of superoxide dismutase and catalase, enzymes which are known to help cells to resist oxidative stress. Additionally, we identify various effects of oligodendroglial exosomes on neuronal physiology. Electrophysiological analysis using in vitro multi-electrode arrays revealed an increased firing rate of neurons exposed to oligodendroglial exosomes. Moreover, gene expression analysis and phosphorylation arrays uncovered differentially expressed genes and altered signal transduction pathways in neurons after exosome treatment. Our study thus provides new insight into the broad spectrum of action of oligodendroglial exosomes and their effects on neuronal physiology. The exchange of extracellular vesicles between neural cells may exhibit remarkable potential to impact brain performance.

1. Introduction

In the central nervous system (CNS), oligodendrocytes wrap axons with a multilayered myelin sheath forming a functional axon–glia unit. Generation and maintenance of this unit requires intense communication between neurons and surrounding glia cells. Classically, intercellular communication is mediated through direct cell–cell contact via gap junctions and adhesion molecules, or secretion of paracrine factors. Recently, additional non-conventional routes of cell–cell communication have been uncovered. Extracellular vesicles (EVs) such as shedding microvesicles (MVs) and exosomes shuttle sets of proteins and RNAs to target cells (for review, see [1]). While MVs directly pinch-off from the plasma membrane, exosomes originate from the endosomal system and are significantly smaller in size (40–100 nm in diameter). They are released into the extracellular space by fusion of multivesicular bodies (MVBs) with the plasma membrane. Cells can use exosomes to dispose of obsolete proteins, but importantly, exosomes...
can also influence the target cell phenotype in various ways [2]. They can protect recipient cells, affect cellular signal transduction, promote malignant transformation and facilitate tumour growth [3]. Furthermore, exosomes contribute to immune responses and spread viruses and pathogenic proteins [4,5]. Exosomal delivery of genetic material, especially mRNA and miRNA, to target cells has gained particular interest. After transfer, mRNAs are translated resulting in newly synthesized proteins in the recipient cells [6]. On the other hand, miRNAs can mediate gene silencing in target cells [7–9].

Oligodendrocytes and all major cell types of the nervous system, including neurons, astrocytes and microglia, release EVs (for review, see [10]). Upon glutamatergic stimulation, cortical neurons secrete exosomes containing the neuronal cell adhesion molecule L1 as well as the AMPA receptor subunits GluR2/3, suggesting a role in synaptic plasticity [11–13]. Exosome release from oligodendrocytes is triggered in a similar way by the neurotransmitter glutamate, which is released by electrically active neurons and acts on oligodendroglial ionotropic glutamate receptors [14]. These exosomes carry a multitude of proteins (e.g. Alix, Tsg101, tetraspanins, heat shock proteins (HSPs) and the myelin proteins PLP and CNP) as well as RNA and are endocytosed by neurons followed by the functional recovery of their cargo. Neurons supplied with exosomes exhibit increased stress tolerance resulting in an improved survival under conditions of oxidative stress or starvation [14]. In addition, oligodendroglial exosomes can act in an autoinhibitory fashion inhibiting myelin formation [15] or, alternatively, become cleared from the extracellular space by microglia in an immunologically silent manner [16]. In the peripheral nervous system, Schwann cells secrete exosomes that are internalized by axons providing local axonal support and enhancing axonal regeneration after nerve damage [17].

In this study, we analyse the versatile impact of oligodendroglial exosomes on neuron physiology using different experimental approaches. We show that exposure of neurons to exosomes increases their action potential firing rate, alters cellular signal transduction pathways, and changes their transcriptome. Moreover, in an in vitro model of ischaemia, oligodendroglial exosomes exert beneficial effects on neurons, potentially via the transfer of protective proteins such as catalase and superoxide dismutase (SOD).

2. Material and methods

(a) Animals and cell culture
Primary cells were prepared from the C57BI/6-N mouse strain. Embryonic day 14 mice of either sex were used for preparation of primary oligodendrocyte (pOL) and primary cortical neuron (pCN) cultures. pOL and the cell line Oli-neu were prepared and cultured in Sato 1% horse serum (HS) as described before [18]. pCN were cultured in Neurobasal feeding medium (Neurobasal (Gibco); 20 ml l⁻¹ B27 (Invitrogen); 0.5 mM L-glutamine; 10 ml l⁻¹ 100× Pen-Strep (63.2 μg ml⁻¹ Penicillin G K-salt; 135 μg ml⁻¹ Streptomycin sulfate)) as described before [19]. O4-positive pOL were prepared from postnatal day 7 mice by using the Neural Tissue Dissociation Kit, gentleMACS dissociator, MACS Separator and anti-O4 MicroBeads (all obtained from Miltenyi Biotec) according to manufacturer’s instructions.

(b) Antibodies and plasmids
The following antibodies were used: rat PLP (clone aa3), rabbit Catalase (Rockland), rabbit βIII-Tubulin (TuJ1; Covance), mouse α-Tub (Sigma), guinea pig doublecortin (DCX; Chemicon), rabbit GFP (green fluorescent protein; Abcam), rabbit phospho-Akt (Cell Signalling), rabbit Akt (Cell Signalling), mouse phospho-Erk1/2 (Cell Signalling), rabbit Erk1/2 (Cell Signalling). The following expression plasmids were used: pEGFP/N1, pEGFP/N1-hSOD1-wt (kind gift of Dr. Albrecht Clement, Mainz, Germany).

(c) Isolation of exosomes
Exosomes were isolated by differential centrifugation of tissue culture supernatants collected from pOL or Oli-neu cells according to standard procedures [20,21]. All steps were carried out at 4 °C. First, dead cells and cell debris were removed by centrifugation for 10 min at 130 g and for 20 min at 10000 g, respectively. Subsequently, the supernatant was centrifuged for 1 h at 100000 g to pellet the exosomes, which were resuspended in 100 μl phosphate-buffered saline (PBS) or recovered from a sucrose cushion (1.8 M sucrose in Tris-buffered saline (TBS)). Nanoparticle tracking analysis of isolated exosomes using the Nanosight LM10 system revealed an average number of 279 ± 12.3 (s.e.m.) × 10⁶ particles of a size between 50 and 120 nm per 1 × 10⁶ pOL (over a collection period of 24 h).

(d) Boyden chamber co-culture
Boyden chamber co-culture was performed as described previously [14]. Briefly, 7 days old pOL (1.25 × 10⁶ per insert) or Oli-neu cells (2 × 10⁵) were co-cultured with pCN (0.7 × 10⁵ per well) in Boyden chambers, which allow contact-free co-culture. Six-well companion plates (353502) and six-well cell culture inserts (353102) were obtained from BD Falcon. To follow exosome transfer, either Oli-neu cells were transfected with 10 μg PLP-EGFP and 10 μg Sirt2-EYFP plasmids, or pOL were stained with the lipophilic dye PKH67 (Sigma) according to the manufacturer’s protocol. Briefly, adherent pOL (4 days in vitro (DIV)) were incubated with 4 μl PKH67 diluted in 1 ml Diluent C for 4 min. Subsequently, reaction was stopped by adding 1 ml PBS + 10% HS for 1 min and cells were extensively washed (five times) with complete medium to remove residual dye. One day later, medium was exchanged and co-culture was started (pOL DIV 7). Immunochemical staining of PKH67-labelled oligodendrocytes confirmed enrichment of the dye in the endosomal system. After 1–2 days of co-culture, pCN were either immunocytochemically stained, lysed and analysed by Western blotting, or alternatively, neuronal RNA was prepared and analysed using microarrays and quantitative reverse transcription polymerase chain reaction (qRT-PCR).

(e) Cell lysates and Western blotting
Cells were scrapped off the culture dish in 10 mM Tris pH 7.4, 150 mM NaCl, 1 mM EDTA, 1% Triton X-100 and protease inhibitor cocktail (Roche complete). Nuclei were pelleted by centrifugation for 10 min at 300 g. Cell lysates and exosome samples were subjected to sodium dodecylsulphate-polyacrylamide gel electrophoresis (SDS-PAGE) and Western blotting (10 or 12 gels, Bio-Rad Mini PROTEAN electrophoresis system). Alternatively, NuPAGE pre-cast gradient (4–12%) gels (Invitrogen) with either MOPS or MES buffer were used according to the manufacturer’s protocol. Western blotting onto a PVDF membrane was performed using Bio-Rad Mini Trans-Blot Electrophoretic Transfer Cell system for 3 h at 300 mA. The membrane was blocked with 4% milk powder/0.1% Tween in PBS. Proteins were detected by sequential incubation of the membrane with primary and horseradish peroxidase-coupled secondary antibodies and developed with enhanced chemiluminescence reagents (Millipore).
(f) Immunocytochemistry
Coverslips were washed with PBS and fixed for 15 min in 4% paraformaldehyde at room temperature. After washing with PBS (3×), cells were permeabilized with 0.1% Triton X100 in PBS for 2 min and washed again with PBS. Cells were then incubated in PBS + 10% HS for at least 15 min before applying the primary antibody diluted in PBS + 10% HS for 1 h. After washing with PBS, the secondary antibody was added diluted in PBS + 10% HS for 30 min. Nuclei were stained with 4′,6-diamidino-2-phenylindole (DAPI) for 2 min. After final washing, the coverslips were briefly submerged in ddH2O before mounting them in Moviol on object slides. Fluorescence images were acquired using a DM6000 fluorescence microscope (Leica).

(g) Microarray and qRT-PCR
pOL (1.25 × 10^6 per insert) and pCN (0.7 × 10^6 per well) were prepared and co-cultured in Boyden chambers for 2 days as described previously [14]. Four individually prepared cultures of pCN were either co-cultured with pOL or with empty inserts containing exosome-depleted conditioned pOL medium as control. After co-culture, total RNA was prepared from pCN using the QiaGen miRNeasy mini Kit according to the manufacturer’s protocol including on-column DNA digestion. Sample preparation for the microarrays was done using the Illumina TotalPrep RNA Amplification Kit including oligo dT primers for cDNA synthesis. For measuring gene expression, the BeadArray Mouse v2 microarray platform from Illumina was used. The microarray data were analysed using R and Bioconductor in particular the ‘limma’ package [22]. For validation of the microarray results, 0.7 × 10^6 pOL (7 DIV) were either co-cultured with 1.25 × 10^6 pOL (7 DIV) for 2 days or treated for 24 h with exosomes released by 8–10 × 10^6 pOL over a time period of 48 h. Subsequently, total RNA was prepared from pCN using the QiaGen miRNeasy mini Kit and qRT-PCR was performed with the StepOne Real-Time PCR System (Applied Biosystems). The results were only taken into account if the average number of active channels (electrodes) was higher than 3. Exosomes released from pOL-conditioned, exosome-depleted medium as described previously [14] were either co-cultured with pOL or with empty inserts containing exosome-depleted conditioned pOL medium as control. After co-culture, total RNA was prepared from pCN using the QiaGen miRNeasy mini Kit and qRT-PCR was performed with the StepOne Real-Time PCR System (Applied Biosystems).

(h) Multi-electrode arrays
pCN were prepared from embryonic day 14 C57BL/6 mouse brains and plated on 6-well-multi-electrode arrays (MEA chips; Multi Channel Systems, Reutlingen, Germany; 2 × 10^5 cells per well). Each well contained 3 × 3 recording electrodes with 200 μm spacing. Exosomes released from 6 to 10 × 10^6 pOL (7 DIV) over a time period of 48 h were prepared, resuspended in 25 μl Neurobasal feeding medium, and applied to one well of pCN (DIV 14). As a control, 25 μl Neurobasal feeding medium alone was applied. The extracellular activity was recorded by using a MEA 1060-INN-BC interface. Recording of the spike activity was started 1 h before exosome treatment and lasted at least 12 h. Only experiments in which neuronal activity was recorded at three or more electrodes were further analysed for spontaneous firing rate, relative burst index and spike amplitude. For further details, see [23,24].

(i) Oxygen—glucose deprivation and analysis of neuronal viability
In Boyden chamber co-culture assays, pCN (10 DIV; 0.7 × 10^6 /6-well) were cultured with O4-positive pOL (1 × 10^6 /insert) for 48 h in Neurobasal/B27 or with blank inserts containing oligodendrocyte-conditioned medium. Before oxygen-glucose deprivation (OGD) exposure, the culture media was replaced by glucose-free Neurobasal and cells were transferred to an anaerobic chamber saturated with 95% N2 and 5% CO2 at 37°C. The cocultures remained in an oxygen-free atmosphere for 2 h in order to mimic an ischaemic condition. Simultaneously, control cultures were grown under normoxic conditions in glucose-containing Neurobasal/B27. To allow subsequent reoxygenation (recovery), cells exposed to the OGD were returned to glucose-containing Neurobasal/B27 and were kept under normoxic conditions for 1 h. Media exchange was equally performed in the normoxic and OGD group. Neuronal viability was determined by the MTT assay. Briefly, 0.75 mg ml^-1 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT, Sigma) was added to culture medium for 2 h. Formazan crystals formed were solubilized in a buffer containing 40% (v/v) dimethyl-formamide (Sigma), 10% (w/v) SDS and 2% (v/v) acetic acid overnight. The absorbance was measured at 562 nm using a plate reader (Tecan Infinite 2000).

3. Results
(a) Oligodendroglial exosomes influence neuronal activity
One of the most basic physiological functions of neurons is to generate action potentials in order to transmit information and communicate with other neurons. Previously, it has been shown that microglia-derived MVs can influence neuronal electrical activity [25]. To test whether oligodendroglial exosomes also have the potential to alter neuronal activity, in vitro MEA recordings were performed. pCNs were cultured on 6-well MEA chips (nine electrodes per well) for 14 days (figure 1a) to allow establishment of neuronal circuits and acquisition of spontaneous electrical activity. Recordings of neuronal spike activity over 6 h are depicted in figure 1b–e. Exosomes derived from cultured pOLs were applied 1 h after recording was started. Subsequently, the relative firing rate (figure 1c), burst index (figure 1d), spike amplitude (figure 1c) and the average channel number per well (figure 1b) were calculated. The results were only taken into account if the average number of active channels (electrodes) was higher.
than three during the recording. While the relative spike amplitude was not changed after application of oligodendroglial exosomes, the relative firing rate increased significantly and immediately (figure 1c). In contrast to the firing rate, the relative burst index decreased slightly after exosome treatment (figure 1d). The relative burst index is a measurement for the synchronicity of the neuronal network activity. A lower burst index indicates that neurons fire in a less synchronized fashion [23,24]. In summary, administration of oligodendroglial exosomes resulted in an increased number of action potentials with unaltered spike amplitude. Concomitantly, exosome-treated neurons fired less synchronously.

(b) Stress protective function of oligodendroglial exosomes

Our previous work revealed that oligodendroglial exosomes have the potential to protect recipient neurons from oxidative stress and ND [14]. To investigate the supportive effects of oligodendroglial exosomes in a diseased background, we used OGD, which is a widely accepted in vitro stroke model. OGD mimics ischaemia resulting in apoptotic and necrotic cell death [26]. pOLs and pCNs were co-cultured in Boyden chambers, allowing a constant supply of the neurons with oligodendroglial exosomes. Control neurons were cultured without oligodendrocytes, but in the presence of oligodendrocyte-conditioned medium depleted of exosomes, to exclude effects mediated by soluble factors. Co-cultures were subjected to OGD followed by a recovery phase and neuronal viability was assessed in relation to normoxic cultures by MTT assay (figure 2a). Intriguingly, neurons grown under ischaemic conditions but supplied with oligodendroglial exosomes revealed a significantly higher metabolic activity compared with control cells (increase of 21.5 ± 7.6%). This indicates that exosomes protect neurons under ischaemic conditions.

A possible mechanism of protection may be that exosome-mediated transfer of enzymes assists the relief of cell stress. Since oxygen radicals form especially during the reperfusion phase [27] after ischaemia, transferred enzymes such as catalase and SOD may reduce oxidative stress. To this end, we investigated the exosome-mediated transfer of these two enzymes to neurons. hSOD1-EGFP expressed in the oligodendroglial cell line Oli-neu is present in exosomes derived from these cells and can be detected in lysates of pCNs co-cultured in Boyden chambers (figure 2b), indicating delivery of hSOD1-EGFP to neurons via oligodendroglial exosomes. Furthermore, catalase can be detected in exosomes isolated from pOLs and catalase protein levels in co-cultured neurons were elevated by 22 ± 5% in coincidence with PLP/DM20 appearing in neurons as a result of exosome transfer (figure 2c,d). By
immunocytochemical staining of neurons co-cultured with oligodendrocytes that were labelled with the dye PKH67, we observed that the signal for catalase was increased, in particular in those neurons that have internalized PKH67-labelled exosomes, suggesting that an exosome-mediated transfer of catalase from oligodendrocytes to neurons may have occurred (figure 2c). However, it is also possible that higher catalase levels in target neurons are due to upregulation of its expression. Taken together, these results suggest that exosomes deliver antioxidant enzymes such as catalase and SOD1, conferring enhanced stress resistance to exosome-recipient neurons.

(c) Activation of signalling pathways by oligodendroglial exosomes

To further elucidate the mechanisms underlying exosome-mediated neuroprotection, we investigated the activation of pro-survival signalling pathways such as MEK/Erk and
PI3K/Akt [28–31] in neurons in response to oligodendroglial exosomes under normal and stress conditions. We first aimed to elucidate the kinetics of kinase activation after exosome addition. Hence, pCNs were treated with purified oligodendroglial exosomes for different time periods (figure 3abc). Subsequent analysis of neuronal lysates by Western blotting revealed the activation of Erk1/2 after 15 min and Akt after 30 min, reaching the maximal phosphorylation level at 15 min and 2 h, respectively (figure 3b). Whether activation of the signalling pathways occurs immediately after binding of exosomes to the cell surface or later during the internalization process will critically influence the activation kinetics.

To test the activation of both pathways under stress, we analysed phosphorylation levels in neurons co-cultured with pOLs in Boyden chambers, which were exposed to oxidative stress or ND (figure 3c,d). Control neurons were cultured without oligodendrocytes, but in oligodendrocyte-conditioned culture supernatant depleted of exosomes. Neurons challenged with either stress exhibited activation of Akt and Erk1/2 when co-cultured with oligodendrocytes (figure 3d). These results suggest that stimulation of Akt and Erk signalling pathways may play a role in exosome-dependent neuroprotection.

To identify additional kinases phosphorylated in neurons due to exosome treatment, we used the Phospho-MAPK (Mitogen-Activated Protein Kinases) Array. pCNs were treated with purified oligodendroglial exosomes or vehicle for 15 h and subsequently subjected to oxidative stress for 1 h. The assay confirmed Akt activation and revealed an exosome-mediated increase in the phosphorylation state of CREB, GSK-3α/β, GSK-3β and JNK, while ERK did not exhibit robust activation under these conditions (figure 3c; highlighted in colours). Thus, oligodendroglial exosomes promote phosphorylation of distinct proteins involved in signalling.

(d) Influence of exosomes on neuronal gene expression
Having shown that exosomes modulate distinct signalling pathways in recipient cells, we analysed potential downstream effects on gene expression. One effect of signalling may be the activation or repression of certain genes, for instance by phosphorylation of the transcription factor cAMP response element-binding protein (CREB; figure 3e). Additionally, exosomes contain distinct mRNAs and miRNAs, which may exhibit pronounced effects on neuronal gene expression [6,7]. To test whether neuronal gene expression is altered by exposure of neurons to oligodendroglial exosomes, we performed a microarray analysis. pCNs were co-cultured in Boyden chambers with pOLs for 2 days. As a control, neurons were cultured in the absence of oligodendrocytes in oligodendrocyte-conditioned, exosome-depleted medium providing all soluble factors released by oligodendrocytes excluding exosomes. Subsequently, neuronal mRNA was prepared and differentially expressed genes were evaluated by microarray analysis. The quality of the raw microarray data was primarily assessed by looking at the spatial distribution of raw intensities on the array surface and by comparing the distribution of bead intensities between the individual arrays (data not shown). The expression data were normalized between the individual samples using the *quantile normalization*, and the data were analysed for differential gene expression using the approach of the R-package limma [34]. A complete list of the most significant differentially regulated genes is displayed in the electronic supplementary material, table S1 (False-Discovery Rate (FDR) ≤ 20%).

A number of selected candidates (table 1) that appeared promising in the context of CNS function were further validated by qRT-PCR in independent biological replicates (figure 4e). Validation revealed significantly altered expression of the following genes: immediate early response 3 (Ier3), cortistatin (Cort), VGF nerve growth factor inducible (Vgf), actin alpha 2 (Act2), cell adhesion molecule with homology to L1CAM (Chl), cyclin-dependent kinase 1 (Cdk1) and brain-derived neurotrophic factor (Bdnf). Moreover, the oligodendrocyte-specific transcripts of PLP, CNP and MBP were detectable in pCNs after co-culture with pOLs. Since the mRNAs of PLP and MBP are present in oligodendroglial exosomes (data not shown), these transcripts may be transferred to neurons.

To confirm that the observed effects can be attributed to exosomes, isolated oligodendroglial exosomes were applied to pCNs and the expression of candidate genes was determined by qRT-PCR (figure 4f). Comparison of the qRT-PCR results derived from the co-cultured and exosome-treated neurons revealed a proportion of likewise regulated genes with statistical significance. Ier3, Vgf and Bdnf are significantly downregulated, while Plp is significantly upregulated in both experimental settings, indicating a robust, exosome-mediated effect. Taken together, these results indicate that oligodendroglial exosomes alter neuronal gene expression and furthermore identify Ier3, Vgf and Bdnf as candidate target genes silenced in response to horizontal exosome transfer from oligodendrocytes to neurons.

(e) Transfer of oligodendroglial exosomes decreases neuronal doublecortin expression
Oligodendroglial exosomes may influence neuronal gene expression by delivery of miRNAs mediating gene silencing. Thus, we investigated the presence of specific miRNAs in oligodendroglial exosomes that had been previously reported in oligodendrocytes [35]. By qRT-PCR, we detected the miRNAs miR-9 and miR-19a in exosomes derived from the oligodendroglial cell line Oli-neu (data not shown). Both miRNAs were predicted to bind DCX (algorithm from www.microRNA.org). DCX is a microtubule-stabilizing protein [36], which is downregulated during neuronal differentiation. To test whether exosome-mediated transfer of these miRNAs influences neuronal DCX expression, we applied oligodendroglial exosomes to cultured pCNs and analysed neuronal DCX levels by Western blotting. Application of exosomes derived from the oligodendrocyte precursor cell line Oli-neu to pCNs (figure 5ad) or Boyden chamber co-culture of pCNs with Oli-neu cells (figure 5bd), likewise resulted in a decreased DCX expression in recipient neurons. To label the glial exosomes, Oli-neu cells ectopically expressed the exosomal proteins Sint2-EYFP and PLP-EGFP, which were also detectable in neuronal lysates and thus served as indicators for exosome transfer (figure 5ab). To the contrary, co-culture with mature pOLs had the tendency to increase neuronal DCX expression (figure 5ac). Taken together, exosomes derived from an oligodendroglial precursor cell line but not from mature oligodendrocytes resulted in decreased neuronal DCX expression in *vivo*.

4. Discussion
This study provides evidence that oligodendroglial exosomes exert a variety of effects on recipient neurons and influence a
Figure 3. Analysis of exosome-dependent signalling pathways in neurons. (a,b) Purified oligodendroglial exosomes were applied to pCN for 0 min, 15 min, 30 min, 1 h, 2 h, 15 h and 24 h. P-Akt and P-Erk1/2 levels determined by Western blotting were normalized to total Akt or Erk and expressed in relation to untreated pCN at timepoint 0 min (n = 2). (c,d) Analysis of exosome signalling in recipient neurons under stress conditions. pCN co-cultured in Boyden chambers with (+) or without (−) pOL for 48 h were subjected to oxidative stress (25 μM H2O2 for 1 h before lysis) or ND (culture in absence of B27 supplement during co-culture) followed by Western blot analysis compared to unstressed cells. (d) Relative P-Akt and P-Erk1/2 levels in pCN are expressed in relation to control cells (−) of each condition to selectively visualize exosome-dependent kinase activation (n = 3). (e) Phospho-MAPK Array for phosphorylated proteins detected in neuronal lysates. pCN were either treated with PBS (control) or purified oligodendroglial exosomes and subjected to oxidative stress (n = 4). Abundance of phosphorylated proteins was quantified by densitometry and compared to PBS-treated pCN (dashed line). Proteins showing a higher phosphorylation level compared to control are highlighted by coloured boxes. Error bars, s.e.m.
Table 1. Neuronal genes regulated in exosome-dependent fashion. Selection of differentially regulated genes detected by microarray analysis (down to a false-discovery rate (FDR) of 20%; n = 4), which were further subjected to qRT-PCR validation. The logFC value is the logarithmic representation of the fold change (FC) value. For a complete list of regulated genes, see the electronic supplementary material, table S1.

<table>
<thead>
<tr>
<th>ID</th>
<th>symbol</th>
<th>description</th>
<th>logFC</th>
<th>FDR (p-value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILMN_2737200</td>
<td>Mbp</td>
<td>myelin basic protein</td>
<td>0.87</td>
<td>$1.79 \times 10^{-7}$</td>
</tr>
<tr>
<td>ILMN_1216764</td>
<td>Ier3</td>
<td>immediate early response 3</td>
<td>$-0.52$</td>
<td>$1.48 \times 10^{-4}$</td>
</tr>
<tr>
<td>ILMN_1221503</td>
<td>Cond1</td>
<td>cyclin D1</td>
<td>$-0.52$</td>
<td>$1.48 \times 10^{-4}$</td>
</tr>
<tr>
<td>ILMN_2601471</td>
<td>Cond1</td>
<td>cyclin D1</td>
<td>$-0.47$</td>
<td>$3.10 \times 10^{-3}$</td>
</tr>
<tr>
<td>ILMN_2955725</td>
<td>Cort</td>
<td>cortistatin</td>
<td>$-0.44$</td>
<td>$3.10 \times 10^{-3}$</td>
</tr>
<tr>
<td>ILMN_1226607</td>
<td>Cort</td>
<td>cortistatin</td>
<td>$-0.42$</td>
<td>$3.10 \times 10^{-3}$</td>
</tr>
<tr>
<td>ILMN_2739843</td>
<td>Metrn</td>
<td>meteorin, glial cell differentiation regulator</td>
<td>$-0.42$</td>
<td>$3.10 \times 10^{-3}$</td>
</tr>
<tr>
<td>ILMN_2754435</td>
<td>Ldb2</td>
<td>LIM domain binding 2</td>
<td>0.38</td>
<td>$1.44 \times 10^{-2}$</td>
</tr>
<tr>
<td>ILMN_2925923</td>
<td>Vgf</td>
<td>VGF nerve growth factor inducible</td>
<td>0.36</td>
<td>$2.52 \times 10^{-2}$</td>
</tr>
<tr>
<td>ILMN_2693895</td>
<td>Acta2</td>
<td>actin, alpha 2, smooth muscle, aorta</td>
<td>0.60</td>
<td>$2.92 \times 10^{-2}$</td>
</tr>
<tr>
<td>ILMN_2670398</td>
<td>Eif4ebp1</td>
<td>eukaryotic translation initiation factor 4E binding protein 1</td>
<td>$-0.35$</td>
<td>$4.64 \times 10^{-2}$</td>
</tr>
<tr>
<td>ILMN_2644008</td>
<td>Chl1</td>
<td>cell adhesion molecule with homology to L1CAM</td>
<td>0.34</td>
<td>$4.72 \times 10^{-2}$</td>
</tr>
<tr>
<td>ILMN_2657844</td>
<td>Cdk1</td>
<td>cyclin-dependent kinase 1</td>
<td>$-0.32$</td>
<td>$7.45 \times 10^{-3}$</td>
</tr>
<tr>
<td>ILMN_3105417</td>
<td>Bdnf</td>
<td>brain-derived neurotrophic factor</td>
<td>$-0.33$</td>
<td>$1.28 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

(a) Oligodendroglial exosomes influence neuronal activity

Here, we demonstrate that treatment of cultured neurons with oligodendroglial exosomes enhances spontaneous neuronal electrical activity. Cultured neurons with already established synaptic connections exposed to exosomes generate more action potentials but at the same time fire in a less synchronized fashion. In general, these findings are consistent with the idea that oligodendrocyte-derived exosomes support the energy metabolism of neurons enabling an increased firing rate. However, the impact of exosomes on neuronal excitability in vivo remains to be proven. An excitatory effect has been reported for microglia-derived MVs that increase spontaneous and evoked excitatory transmission in hippocampal neurons [25]. Microglia-derived MVs act at the presynaptic site of the excitatory synapse by increasing the release probability of synaptic vesicles through induction of sphingolipid metabolism. A similar mechanism could be responsible for the increase of neuronal activity by oligodendrocyte-derived exosomes.

(b) Stress protective function of oligodendroglial exosomes

We have demonstrated previously that oligodendroglial exosomes ship protective cargo to neurons increasing their resistance against oxidative stress and starvation [14]. Here, we add further evidence that exosomes are also protective during OGD, which is a well-established in vitro model of cerebral ischaemia [40]. During brain ischaemia, the extracellular glutamate concentration increases, which can lead to neuronal cell death [40,41]. Exosome release from mature oligodendrocytes is actually triggered by glutamate [14], which in fact may help to prevent neuronal cell death during stroke, confining the ischaemic insult. Putative...
candidates exhibiting supportive function when transferred via exosomes may include HSPs as well as proteins involved in the oxidative stress response, like catalase and SOD. The role of HSPs in neuroprotection is well established and it has been previously shown that they can be supplemented from adjacent glial cells [42–45]. Our recent findings indicate that Hsc/Hsp70 [14], catalase and SOD1 are present in oligodendroglial exosomes and transferred to neurons. Since catalase mediates the breakdown of H$_2$O$_2$ to water and oxygen, this enzyme supplied to neurons by adjacent oligodendrocytes may protect neurons from H$_2$O$_2$-induced oxidative stress. Catalase is a peroxisome-resident protein and it may be interesting to note that intact peroxisomes in oligodendrocytes are required to maintain axon integrity in vivo [46]. SOD is another important enzyme involved in the antioxidant defence acting upstream of catalase by catalysing the dismutation of superoxide into oxygen and H$_2$O$_2$. It has been demonstrated previously that

Figure 4. Validation of exosome-dependent neuronal gene regulation. qRT-PCR analysis of candidate genes selected from microarray analysis. (a) pCN co-cultured in Boyden chambers with pOL compared to control pCN (n = 6; BDNF and PLP, n = 14). (b) pCN treated with isolated pOL-derived exosomes compared to untreated pCN (n = 7; BDNF, PLP, MBP and CNP, n = 5). Pgk1 was used as normalization standard. Log2 values of the $\Delta\Delta$Ct values are displayed. Genes validated in both paradigms as downregulated or upregulated are indicated by red bars (dark grey in print) and green bars (light grey in print), respectively. Error bars, s.e.m. (n.s., not significant; *p < 0.05; **p < 0.01; Wilcoxon test). (Online version in colour.)
wild-type human SOD1 as well as their mutant forms are released in association with exosomes [47,48], which may be implicated in ALS pathogenesis.

(c) Activation of signalling pathways by oligodendroglial exosomes

Oligodendroglial exosomes contribute to neuronal survival under distinct stress conditions. However, the molecular determinants of enhanced survival are still unknown. Here, we identify several kinases that are activated in the target neurons upon treatment with oligodendroglial exosomes under normal as well as stress conditions. Cellular phosphorylation levels of Akt and Erk1/2 kinases are enhanced within minutes in response to oligodendroglial exosomes. Erk exhibited faster activation kinetics compared with Akt, indicating that it may act more upstream in the signalling cascade. Both kinases have been implicated in promoting survival [28–31]. In addition to Akt and Erk1/2, we identified CREB, GSK-3α/β, GSK-3β and JNK as phosphorylated in response to oligodendroglial exosomes. CREB is present in all cells of the CNS and functions as a transcription factor promoting cell survival and, furthermore, has a well-documented role in neuronal plasticity and the transcriptional control of memory formation [49–51]. Intriguingly, the Akt pathway activates CREB and downstream targets of CREB include the transcripts of BDNF and VGF [52–55], which we identified to be significantly regulated in neurons exposed to oligodendroglial exosomes. Additionally, phosphorylation of GSK-3α/β and GSK-3β, further downstream targets of Akt [56], may contribute to the neuroprotective function of oligodendroglial exosomes [57–59]. JNKs (c-Jun N-terminal kinases) are stress-induced protein kinases with various functions [60,61]. Recently, it has been reported that activated JNK is required for axon formation [62]. The transcription factor ATF-2, a member of the ATF/CREB family, is a target of JNK and was suggested to play a role in neuronal survival [62–64]. Taken together, these results reveal a variety of pathways potentially involved in mediating the neuroprotective effect of oligodendroglial exosomes. It is open at present whether signalling pathway activation requires exosome endocytosis or whether cell surface binding of exosomes is sufficient to elicit signalling.

Figure 5. Downregulation of DCX in neurons in response to exosomes derived from oligodendrocyte precursor cells. (a–c) Western blot analysis of neuronal lysates. (a) pCN were treated with exosomes isolated from Oli-neu cells ectopically expressing Sirt2-EYFP and PLP-EGFP for 2 and 24 h, respectively (n = 6). (b,c) Boyden chamber co-culture of pCN either with Oli-neu cells ectopically expressing Sirt-EYFP and PLP-EGFP (b, n = 4) or with pOL and Oli-neu (c, n = 6) for 2 days. (d) Doublecortin (DCX) expression levels normalized to tubulin (Tub) as quantified from Western blots. Control pCN (untreated) are referred to as 100%. Error bars, s.e.m. (*p < 0.05; **p < 0.01; ***p < 0.001; Students t-test).
In this study, we provide evidence that oligodendroglial exosomes exhibit versatile effects on neuronal physiology. We identify exosomes as signalling entity in the brain able to influence neurons in multiple ways. However, we are only beginning to understand these effects, and future studies are needed to unravel the detailed mechanisms. Elucidating these mechanisms will enhance our understanding of brain performance in health and disease.

Acknowledgements. We thank Lilja Niedens for technical help, Bruno Kyewski for support and Albrecht Clement for reagents.

Funding statement. This study was supported by the DFG (grant KR 3668/1–1 to E.M.K.A.). C.F. received internal research funding for early career researchers from JGU Mainz. D.F. and W.P.K. received stipends from the Stipendiens Stiftung Rheinland Pfalz, the Kalkhof-Rose Foundation and the Focus Program Translational Neuroscience JGU Mainz, respectively.

References


(d) Influence of exosomes on neuronal gene expression

Initiation of signalling pathways in recipient neurons may result in differentially expressed genes. In addition, exosomal mRNAs and miRNAs or transcription factors are likely to modify the neuronal transcriptome. However, the ability to modify neuronal gene expression by the release of exosomes enables oligodendrocytes to broadly modulate the phenotype of surrounding neurons.

The most significantly regulated genes are Plp, Ier3, Vgf and Bdnf. Since PLP mRNA can be found in oligodendroglial exosomes, the upregulation of Plp may be a consequence of exosomal transfer of PLp mRNA. It has been reported previously that mRNA is transferred between mast cells by the means of exosomes and translated into functional proteins within the target cells [6]. Knockdown of Ier3, Vgf and Bdnf may be a result of transferred miRNAs. The transfer of miRNAs and the subsequent knockdown of their target genes have been shown before [7]. Ier3 belongs to the immediate early genes that are induced by a variety of stimuli such as growth factors, cytokines, ionizing radiation, viral infection and other kinds of cellular stress [65]. IER3 plays a complex and contradictory role in apoptosis and cell cycle control depending on the cellular context and growth conditions [65]. Both VGF and BDNF belong to the class of growth factors and are essential mediators of neuronal development, survival, axonal outgrowth and synaptic plasticity. BDNF plays a role in hippocampal-dependent associative memory [66], neurogenesis of hippocampal neurons [67] and during the pathology of depression [68]. BDNF induces the expression of Vgf via the transcription factor CREB [69]. Thus, reduced Vgf levels may be a consequence of decreased Bdnf expression. VGF is further processed into distinct peptides, which are subsequently released and exhibit a variety of functions, for instance the regulation of hippocampal synaptic plasticity and depressive behaviour in rodents [70,71]. However, the results indicate that oligodendroglial exosomes have the potential to influence neuronal physiology on a broad spectrum by regulating neuronal gene expression either via induction of distinct signalling pathways or by the selective transfer of mRNAs and miRNAs.

(e) Transfer of exosomes decreases neuronal doublecortin expression

Uptake of exosomes derived from the oligodendroglial precursor cell line Oli-neu but not from mature oligodendrocytes leads to a decreased DCX expression in recipient neurons, possibly by the transfer of glial miRNAs. We found the miRNAs miR-9 and miR-19a with predicted binding to DCX in oligodendroglial exosomes. It has been shown before that expression of both miRNAs is downregulated during oligodendrocyte maturation [35]. This is consistent with the finding that transfer of exosomes derived from the oligodendrogial precursor cell line Oli-neu but not from mature oligodendrocytes decreases neuronal DCX expression. DCX is a microtubule-stabilizing protein, which is mainly expressed by neuronal precursor cells and immature neurons [36]. Decreased DCX expression is associated with neuronal maturation and differentiation. The exosome-mediated down-regulation of DCX may be important during development, where oligodendroglial exosomes could provide a differentiation signal to neurons, either initiating differentiation of neuronal precursor cells or keeping mature neurons in a differentiated state. Alternatively, neuronal precursors that migrate from the subventricular zone to the olfactory bulb along the rostral migratory stream could start to differentiate once they have come into contact with exosomes. And finally, oligodendroglial precursors accumulate at CNS injuries [72] and may be involved in on-going repair processes of the adult brain by stimulating axonal regeneration via the secretion of exosomes.

5. Conclusion

In this study, we provide evidence that oligodendroglial exosomes exhibit versatile effects on neuronal physiology. We identify exosomes as signalling entity in the brain able to influence neurons in multiple ways. However, we are only beginning to understand these effects, and future studies are needed to unravel the detailed mechanisms. Elucidating these mechanisms will enhance our understanding of brain performance in health and disease.


59. Chin PC, Majzdladzeh N, D’Mello SR. 2005 Inhibition of GSK3beta is a common event in neuroprotection by different survival factors. Brain Res. Mol. Brain Res. 137, 193 – 201.


68. Shimizu E et al. 2003 Alterations of serum levels of brain-derived neurotrophic factor (BDNF) in depressed patients with or without antidepressants. Biol. Psychiatry 54, 70 – 75.


