Astrocytes with TDP-43 inclusions exhibit reduced noradrenergic cAMP and Ca\(^{2+}\) signaling and dysregulated cell metabolism

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Most cases of amyotrophic lateral sclerosis (ALS) and frontotemporal dementia (FTD) have cytoplasmic inclusions of TAR DNA-binding protein 43 (TDP-43) in neurons and non-neuronal cells, including astrocytes, which metabolically support neurons with nutrients. Neuronal metabolism largely depends on the activation of the noradrenergic system releasing noradrenaline. Activation of astroglial adrenergic receptors with noradrenaline triggers cAMP and Ca\(^{2+}\) signaling and augments aerobic glycolysis with production of lactate, an important neuronal energy fuel. Astrocytes with cytoplasmic TDP-43 inclusions can cause motor neuron death, however, whether astroglial metabolism and metabolic support of neurons is altered in astrocytes with TDP-43 inclusions, is unclear. We measured lipid droplet and glucose metabolisms in astrocytes expressing the inclusion-forming C-terminal fragment of TDP-43 or the wild-type TDP-43 using fluorescent dyes or genetically encoded nanosensors. Astrocytes with TDP-43 inclusions exhibited a 3-fold increase in the accumulation of lipid droplets versus astrocytes expressing wild-type TDP-43, indicating altered lipid droplet metabolism. In these cells the noradrenaline-triggered increases in intracellular cAMP and Ca\(^{2+}\) levels were reduced by 35% and 31%, respectively, likely due to the downregulation of \(\beta\)-adrenergic receptors. Although noradrenaline triggered a similar increase in intracellular lactate levels in astrocytes with and without TDP-43 inclusions, the probability of activating aerobic glycolysis was facilitated by 1.6-fold in astrocytes with TDP-43 inclusions and lactate MCT1 transporters were downregulated. Thus, while in astrocytes with TDP-43 inclusions noradrenergic signaling is reduced, aerobic glycolysis and lipid droplet accumulation are facilitated, suggesting dysregulated astroglial metabolism and metabolic support of neurons in TDP-43-associated ALS and FTD.

Amyotrophic lateral sclerosis (ALS) is a neurodegenerative disorder characterized by the loss of both upper and lower motor neurons in the brain and spinal cord, and by the progressive paralysis of voluntary muscles and death\(^{1,2}\). The pathologic hallmark of ALS are cytoplasmic inclusions in motor neurons. In most cases (~95%) of sporadic and familial ALS, TAR DNA-binding protein 43 (TDP-43), encoded by the \(TARDBP\) gene, has been identified as the key component of these inclusions\(^{1–9}\). Moreover, TDP-43 has also been identified as the major protein in inclusions in frontotemporal dementia with ubiquitin-positive inclusions (FTD-U)\(^{9,10}\).

TDP-43 is a highly conserved protein (414 amino acids), ubiquitously expressed in all tissues and under physiological conditions, primarily localized to the nucleus; however, low levels are also present in the cytoplasm\(^{3,8,10–11}\). TDP-43, an RNA-binding protein, is implicated in multiple aspects of RNA processing, including regulation of transcription, splicing, transport, and stabilization of mRNAs. It also regulates microRNA biogenesis and interacts with DNA. Therefore, its perturbation may lead to significant changes in the transcriptome and

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proteome. It consists of an N-terminal domain, two RNA recognition motifs and a C-terminal prion-like glycine-rich domain that mediates protein-protein interactions with other heterogeneous ribonucleoprotein (hnRNP) family members.

In most pathologic cases, TDP-43 is hyperphosphorylated and ubiquitinated. Although ubiquitination targets TDP-43 aggregates for degradation, TDP-43 begins to accumulate in the cytoplasm, suggesting that additional perturbation in either the ubiquitin-proteasome system or the autophagy pathway can facilitate the accumulation of TDP-43 in ALS and FTD-U. 25-kDa C-terminal fragments of TDP-43 (TDP-43<sub>208-414</sub>) are commonly detected in ALS and FTD-U pathologic specimens, especially in the cerebral cortex, and generation of these fragments is sufficient to initiate a number of events that mirror TDP-43 proteinopathies.

TDP-43-containing cytoplasmic inclusions are not restricted to motor neurons but are also found in non-neuronal cells, in particular in astrocytes. Astrocytes with TDP-43 inclusions are sufficient to cause motor neuron death in animal models and exhibit autotoxicity. Thus, astrocytes were recently proposed to play an active role in controlling ALS disease progression and may even be the primary driver of TDP-43 proteinopathies.

Astrocytes are an abundant and heterogeneous subtype of neuroglia in the central nervous system (CNS), regulating CNS metabolism. With their numerous processes, they are in tight contact with neurons, including motor neurons, and blood vessels. They transport nutrients from the blood stream to neurons and store blood-derived glucose in the form of glycogen as the CNS fuel reserve and perhaps also as free glucose in endoplasmic reticulum. Astrocytes are considered an important cellular target of noradrenaline (NA), released from the locus coeruleus (LC) noradrenergic neurons, which regulates CNS energy metabolism. NA binds to G-protein-coupled adrenergic receptors (ARs, α<sub>1</sub>-AR, α<sub>2</sub>-AR and β<sub>2</sub>-AR) on the surface of brain cells, including astrocytes, where ARs are abundantly expressed, changing cyclic AMP (cAMP) and cyclic adenosine monophosphate ([cAMP]) and Ca<sup>2+</sup> ([Ca<sup>2+</sup>]) levels. This activates astroglial metabolism, which is mainly controlled by β-AR/cAMP signaling, enhancing glucose uptake, glycogenolysis, aerobic glycolysis, and lactate production. Lactate is considered to be then shuttled to neurons where it is used as fuel by being transformed to pyruvate and entering oxidative phosphorylation.

In vitro and in vivo studies using ALS model systems of superoxide dismutase 1 (SOD1)-related familial ALS have provided first evidence of metabolic dysfunction in ALS astrocytes, particularly in the transporter responsible for the efflux of lactate, dysfunctional astrocytic mitochondria, and lower levels of intracellular lactate upon exposure of astrocytes to glutamate. Besides glucose metabolism, lipid metabolism might also be impaired in neurons and astrocytes during neurodegeneration as observed in animal models. If reactive oxygen species (ROS) are elevated in the brain like during neurodegeneration, the glia-neuron lactate shuttle is believed to promote lipid synthesis in neurons. Peroxidized and potentially cytotoxic lipids are then shuttled via apolipoproteins (apo) E and D and fatty acid transport proteins, from neurons to glial cells, causing accumulation of lipid droplets (LDs) in glial cells, dynamic organelles, undergoing regulated, stress-induced biogenesis and/or degradation, that play an important role in intracellular lipid metabolism and storage. Consistent with the observations in animal models, a reduced glucose uptake and increased glycolysis have been observed in the CNS of patients with ALS; both processes highly depend on astrocytes, suggesting alterations in astroglial metabolism. Whether TDP-43 inclusions, a hallmark of ALS and FTD-U pathologies, can in astrocytes alter metabolism, in particularly LD and glucose metabolisms, we transfected primary cortical astrocytes with the pDNA encoding RFP-tagged C-terminal fragment of TDP-43 (RFP-TDP-43<sub>208–414</sub>), known to generate cytoplasmic inclusions in other cell types, or with the pDNA encoding RFP-tagged WT TDP-43 (RFP-TDP-43<sub>wt</sub>). Using confocal microscopy, we observed that in astrocytes expressing the RFP-TDP-43<sub>wt</sub> construct, the RFP signal is visible mainly in the cell nucleus (Fig. 1B), whereas in RFP-TDP-43<sub>208–414</sub>-expressing astrocytes, red fluorescent inclusions, typical for ALS and FTD-U pathologies, are observed in the cytoplasm.

**Results**

**Overexpression of TDP-43<sub>208–414</sub> in astrocytes causes cytoplasmic inclusions and lowers the amount of endogenous nuclear TDP-43.** To study how ALS- and FTD-U-associated TDP-43 inclusions in astrocytes affect cell metabolism, in particularly LD and glucose metabolisms, we transfected primary cortical rat astrocytes with the pDNA encoding RFP-tagged C-terminal fragment of TDP-43 (RFP-TDP-43<sub>208–414</sub>), known to generate cytoplasmic inclusions in other cell types, or with the pDNA encoding RFP-tagged WT TDP-43 (RFP-TDP-43<sub>wt</sub>). Using confocal microscopy, we observed that in astrocytes expressing the RFP-TDP-43<sub>208–414</sub> construct, the RFP signal is visible mainly in the cell nucleus (Fig. 1B), whereas in RFP-TDP-43<sub>208–414</sub>-expressing astrocytes, red fluorescent inclusions, typical for ALS and FTD-U pathologies, are observed in the cytoplasm.
Figure 1. Nuclear RFP-TDP-43<sup>wt</sup> and cytoplasmic RFP-TDP-43<sup>208–414</sup> expression in cultured cortical rat astrocytes. (A–C) Representative fluorescence images of astrocytes immunostained with antibodies against endogenous TDP-43 (green) and labelled with DAPI (blue) in (A) control (non-transfected), (B) RFP-tagged wild-type TDP-43-expressing astrocytes (RFP-TDP-43<sup>wt</sup>; red) and (C) RFP-tagged C-terminal fragment of TDP-43-expressing astrocytes (RFP-TDP-43<sup>208–414</sup>; red). Note the red fluorescent inclusions in the cytoplasm of astrocytes expressing RFP-TDP-43<sup>208–414</sup> and nuclear expression of RFP-TDP-43<sup>wt</sup>. Scale bar, 20 µm. (D) Colocalization (%) between RFP fluorescence signal (red) and Alexa Fluor<sup>488</sup>-labelled TDP-43 antibody (green) in astrocytes transfected with RFP-TDP-43<sup>wt</sup> or RFP-TDP-43<sup>208–414</sup>. (E) Colocalization (%) between the total cellular TDP-43 antibody signal and the nuclear DAPI stain in control cells and in cells transfected with RFP-TDP-43<sup>wt</sup> or RFP-TDP-43<sup>208–414</sup>. Note the low percentage of TDP-43 antibody colocalization with the nuclear DAPI stain in RFP-TDP-43<sup>208–414</sup>-expressing astrocytes, indicating that in these cells, most of the TDP-43 protein resides in the cytoplasm. (F) The percentage (%) of DAPI and TDP-43-colabeled nuclei in non-transfected astrocytes (no visible RFP signal) in control experimental group (Control; n = 99 cells from 28 images) and in non-transfected astrocytes around the astrocytes expressing the RFP-constructs in RFP-TDP-43<sup>wt</sup> (n = 62 cells from 18 images), and RFP-TDP-43<sup>208–414</sup> (n = 77 cells from 19 images) experimental groups. The numbers by the error bars indicate the number of cells (D, E) or number of cell nuclei (F) analysed. Data are presented as means ± SEM and acquired from at least two different animals. Each experiment (i.e. coverslip) was performed in duplicate, multiple cells were recorded per coverslip. ***P ≤ 0.001, Mann-Whitney U test (D); ***P ≤ 0.001, Kruskal-Wallis one-way ANOVA on ranks, followed by Dunn’s test (E).
Lipid droplet content is increased in the cytoplasm of TDP-43<sub>208–414</sub>-expressing astrocytes. To evaluate whether the expression of the ALS- and FTD-U-linked C-terminal fragment of TDP-43 affects accumulation of argyrophilic LDs, we stained non-transfected cells and cells expressing RFP-TDP-43<sup>wt</sup> and RFP-TDP-43<sup>208–414</sup> with a fluorescent LD marker BODIPY<sup>493/503</sup> (Fig. 2). The expression of RFP-TDP-43<sup>208–414</sup> (n = 41) in astrocytes increased the amount of BODIPY<sup>493/503</sup>-positive cell cross-sectional area, indicating LD content increase, by ~4- and ~3-fold compared with control non-transfected (n = 58) and RFP-TDP-43<sup>wt</sup>-expressing astrocytes, respectively (n = 41; Fig. 2B; P < 0.001). Moreover, the average number of LDs per cell (32.0 ± 4.1 (RFP-TDP-43<sup>wt</sup>) versus 74.7 ± 6.7 (RFP-TDP-43<sup>208–414</sup>), P < 0.001), LD perimeter (1.6 ± 0.1 μm (RFP-TDP-43<sup>wt</sup>) versus 2.3 ± 0.1 μm (RFP-TDP-43<sup>208–414</sup>), P < 0.001), and LD diameter (0.50 ± 0.02 μm (RFP-TDP-43<sup>wt</sup>) versus 0.74 ± 0.03 μm (RFP-TDP-43<sup>208–414</sup>), P < 0.001), increased in astrocytes with TDP-43<sup>208–414</sup>clusions (Fig. 2C–E), indicating an increase in the accumulation of LDs.

A small amount of TDP-43 inclusions in some cells can be seen inside the DAPI-labeled nuclear area, thus the role of nuclear TDP-43 inclusions on the accumulation of LDs cannot be excluded. However, since the thickness of the optical section of an individual confocal image was relatively large (1.2 μm) enabling the nuclear and cytoplasmic fluorescence signals to overlap, it is more likely that the TDP-43 inclusions seen at the DAPI-labeled nuclear area are in fact located in the cytosol.

Noradrenaline-mediated increases in [cAMP], and [Ca<sup>2+</sup>], are reduced in TDP-43<sup>208–414</sup>-expressing astrocytes. Astrocytes appear to be the primary target of NA, an important neuromodulator in the CNS<sup>38–40</sup>. Through binding to ARs on the surface of astrocytes, NA activates CAMP and Ca<sup>2+</sup> signaling<sup>37,39,56</sup>, which may be dysregulated in various neurologic disorders<sup>32,57–60</sup>. To study whether ALS- and FTD-U-linked TDP-43 inclusions affect CAMP and Ca<sup>2+</sup> signaling, we monitored NA-induced changes in [cAMP], and [Ca<sup>2+</sup>]<sup>+</sup>, using real-time confocal microscopy and genetically encoded FRET-based CAMP nanosensor Epac1-camps<sup>37</sup> or Fluor-4 AM dye, respectively, in astrocytes expressing WT (RFP-TDP-43<sup>wt</sup>) or mutant TDP-43<sup>208–414</sup> pDNA construct (RFP-TDP-43<sup>208–414</sup>, Figs. 3 and 4 and Online resource 1, Fig. S1).

The percentage of astrocytes co-expressing both Epac1-camps and RFP-TDP-43<sup>wt</sup> or RFP-TDP-43<sup>208–414</sup> construct was 68.4% (n = 54/79) or 44.7% (n = 42/94), respectively (Online resource 1, Fig. S1; Table 1). Only astrocytes that co-expressed Epac1-camps and RFP-TDP-43<sup>208–414</sup> pDNA constructs were used in the experiments. The addition of NA (100 μM), a non-selective α<sub>1</sub>–β-AR agonist, induced an exponential increase in the Epac1-camps FRET signal (CFP/YFP), likely reflecting a β-AR-mediated increase in [cAMP]<sup>37,39</sup> in both RFP-TDP-43<sup>wt</sup>(n = 9) and RFP-TDP-43<sup>208–414</sup>-expressing astrocytes (n = 9; Fig. 3B; Table 2). The mean amplitude change in the FRET signal (mean ΔFRET [%]) and the mean time constant (τ) in astrocytes expressing RFP-TDP-43<sup>wt</sup> were 27.1 ± 3.6% and 19.9 ± 2.7 s, respectively (Fig. 3C,D), not significantly different from control, Epac1-camps-expressing astrocytes (Online resource 1, Fig. S2A; P = 0.43 [ΔFRET] and P = 0.63 [τ])<sup>37</sup>, indicating that the overexpression of RFP-TDP-43<sup>wt</sup> and RFP-tagging of the TDP-43<sup>wt</sup> does not affect NA-mediated CAMP signals in astrocytes. However, the NA-mediated increase in [cAMP], was significantly reduced in RFP-TDP-43<sup>208–414</sup>-expressing astrocytes, as reflected by the reduced amplitude in the FRET signal (~18% versus ~27%, respectively; P < 0.05; Fig. 3C). Similarly, the time constant of the FRET signal increase was significantly slower in RFP-TDP-43<sup>208–414</sup> versus RFP-TDP-43<sup>wt</sup>-expressing astrocytes.
(10.7 ± 1.6 s versus 19.9 ± 2.7 s, respectively; P < 0.05; Fig. 3D). Resting levels of cAMP in RFP-TDP-43208–414- and RFP-TDP-43wt-expressing astrocytes were unchanged (not shown). Thus, noradrenergic stimulation leading to the β-AR-mediated increase in [cAMP], is reduced in astrocytes expressing the ALS- and FTD-U-related C-terminal fragment of TDP-43 (amino acids 208–414) compared with astrocytes expressing WT TDP-43.

Next, astrocytes expressing RFP-TDP-43wt or RFP-TDP-43208–414 were labeled with Ca²⁺ indicator, Fluo-4 AM dye, and treated with NA (100 µM; Fig. 4). Application of NA elicited rapid increase in Fluo-4 AM fluorescence (ΔF) that after reaching a peak started to decrease towards the baseline level both in RFP-TDP-43wt- and RFP-TDP-43208–414-expressing astrocytes (Fig. 4B), reflecting increase in [Ca²⁺], likely through activation

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**Figure 2.** Astrocytes expressing RFP-TDP-43208–414 have an increased lipid droplet content compared with RFP-TDP-43wt-expressing astrocytes. (A) Representative fluorescence images of non-transfected astrocytes (control; upper panels) and astrocytes transfected with RFP-tagged TDP-43wt (middle panels) or TDP-43208–414 (lower panels) plasmids (red) and stained with fluorescent lipid droplet (LD) marker BODIPY493/503 (BODIPY, green). BODIPY493/503 staining was performed 25 h after transfection with pDNA constructs. Nuclei are labelled with DAPI (blue). TL: transmission light. Scale bar, 20 µm. (B–E) Histogram of BODIPY493/503-positive cell cross-sectional area (lipid droplet S; i.e. number of green fluorescence pixels with fluorescence intensity above the threshold of 20% of maximal fluorescence) versus total cell cross-sectional area (cell S; i.e. number of all pixels; B), average LD number per cell (C), LD perimeter (D), and LD diameter (E) in control, RFP-TDP-43wt- and RFP-TDP-43208–414-expressing cells. Numbers adjacent to the error bars indicate the number of cells analysed. Data are presented as means ± SEM and acquired from at least two different animals. Each experiment (i.e. coverslip) was performed in duplicate, multiple cells were recorded per coverslip. Asterisks denote statistically significant differences (***P < 0.001, Kruskal-Wallis one-way ANOVA on ranks, followed by Dunn's test).
The mean peak amplitude and the cumulative Ca\textsuperscript{2+} response were, however, significantly lower in astrocytes expressing RFP-TDP-43\textsuperscript{208–414} (3.2 ± 0.3 ΔF/F\textsubscript{0} [RFP-TDP-43\textsuperscript{wt}; n = 55] versus 2.6 ± 0.2 ΔF/F\textsubscript{0} [RFP-TDP-43\textsuperscript{208–414}; n = 162; P < 0.05] and 98.5 ± 15.2 ΔF/F\textsubscript{0} [RFP-TDP-43\textsuperscript{wt}; n = 55] versus 68.1 ± 7.2 ΔF/F\textsubscript{0} [RFP-TDP-43\textsuperscript{208–414}; n = 162; P < 0.05]; respectively; Fig. 4C,D).

These results show that NA-mediated cAMP and Ca\textsuperscript{2+} signaling are attenuated in astrocytes with ALS- and FTD-U-linked TDP-43 inclusions.
Responsiveness of cells to noradrenaline-induced lactate production was higher in TDP-43208–414-expressing astrocytes compared with TDP-43wt-expressing astrocytes. Noradrenergic signaling regulates glucose metabolism, in particular aerobic glycolysis and lactate production, which may be altered in ALS. This may affect astrocyte-neuron lactate shuttle and astrocytic metabolic support of neurons. Because NA-mediated cAMP signaling is reduced in astrocytes overexpressing RFP-TDP-43208–414, we asked whether RFP-TDP-43208–414 overexpression affects the NA-mediated increase in aerobic glycolysis and therefore lactate production. To monitor real-time changes in lactate concentration in response to NA, cultured rat astrocytes expressing RFP-TDP-43wt or RFP-TDP-43208–414 were co-transfected with the FRET-based nanosensor Laconic (Fig. 5).

Figure 4. Noradrenaline-mediated Ca2+ response is reduced in astrocytes expressing RFP-TDP-43208–414 compared with RFP-TDP-43wt-expressing astrocytes. (A) Representative fluorescence images of RFP-TDP-43wt-expressing astrocytes labeled with Ca2+ indicator Fluo-4 AM and stimulated with noradrenaline (NA, black line). Scale bar: 20 µm. (B) Mean intensity changes in intracellular Ca2+ ([Ca2+]i) upon stimulation with 100 µM NA (black line) in astrocytes expressing RFP-TDP-43wt (n = 55; black circles) and RFP-TDP-43208–414 (n = 162; gray circles). Each data point represents the mean ± SEM. (C, D) Mean peak amplitude (C) and cumulative Ca2+ response (D) upon the addition of NA for RFP-TDP-43wt and RFP-TDP-43208–414 experimental groups. Numbers adjacent to the error bars depict the number of cells analysed. Data are presented as means ± SEM and acquired from four different animals (multiple cells were recorded per coverslip). Asterisk denotes statistical significance, *P < 0.05, determined by the Mann-Whitney U test.

Table 1. The percentage of astrocytes (co)expressing Epac1-camps and RFP-tagged TDP-43 constructs 30 h after transfection of cells with Epac1-camps and either RFP-TDP-43wt or RFP-TDP-43208–414 pDNA constructs. Epac1-camps, cAMP nanosensor; RFP-TDP-43wt, RFP-tagged TDP-43 wild-type; RFP-TDP-43208–414, RFP-tagged C-terminal fragment (amino acids 208–414) of TDP-43; n, number of cells. aAstrocytes were expressing either Epac1-camps, RFP-TDP-43wt or RFP-TDP-43208–414. bAstrocytes were co-expressing Epac1-camps with either RFP-TDP-43wt or RFP-TDP-43208–414.

Responsiveness of cells to noradrenaline-induced lactate production was higher in TDP-43208–414-expressing astrocytes. In astrocytes, noradrenergic signaling regulates glucose metabolism, in particular aerobic glycolysis and lactate production, which may be altered in ALS. This may affect astrocyte-neuron lactate shuttle and astrocytic metabolic support of neurons. Because NA-mediated cAMP signaling is reduced in astrocytes overexpressing RFP-TDP-43208–414, we asked whether RFP-TDP-43208–414 overexpression affects the NA-mediated increase in aerobic glycolysis and therefore lactate production. To monitor real-time changes in lactate concentration in response to NA, cultured rat astrocytes expressing RFP-TDP-43wt or RFP-TDP-43208–414 were co-transfected with the FRET-based nanosensor Laconic (Fig. 5). As in the experiments with Epac1-camps, only astrocytes expressing both Laconic and RFP-TDP-43 pDNA constructs were used in the analysis.
The expression of MCT1 transporters was significantly lower in astrocytes expressing RFP-TDP-43Δ208–414 (4.2% RFP-TDP-43wt (31.8% versus 42.8%, respectively). The responsiveness of astrocytes to NA-induced lactate production was similar to that in astrocytes expressing TDP-3R208–414-expressing astrocytes (84.0% RFP-TDP-43wt versus 60.0% RFP-TDP-43Δ208–414; Table 2, Fig. 5D). The mean amplitude and the initial rate of the Laconic FRET signal increase were 1.6-fold and 2-fold lower, respectively, but statistically insignificantly different, in the RFP-TDP-43Δ208–414 than in the RFP-TDP-43wt-expressing astrocytes (2.6 ± 0.5% [RFP-TDP-43wt; n = 16] versus 1.6 ± 0.2% [RFP-TDP-43Δ208–414; n = 9; P = 0.02] and 2.2 ± 1.2%/min [RFP-TDP-43wt; n = 16] versus 1.1 ± 0.1%/min [RFP-TDP-43Δ208–414; n = 9; P = 0.4]; respectively; Fig. 5B, Table 2).

The overexpression of TDP-43Δ208–414 reduces the expression of β2-adrenergic receptors in astrocytes. Because the expression of RFP-TDP-43Δ208–414 causes a reduction in NA-mediated cAMP and Ca2+ signaling compared with cells expressing RFP-TDP-43wt, we next investigated whether the overexpression of RFP-TDP-43Δ208–414 alters the expression of ARs. Astrocytes express all types of ARs33,34,63. We immunostained astrocytes expressing RFP-TDP-43wt and RFP-TDP-43Δ208–414 with antibodies against MCT1 and MCT4 transporters (Fig. 7). The expression level of astrocyte-specific monocarboxylate transporters (MCT), which are in astrocytes predominantly responsible for L-lactate transport across the plasma membrane, was reduced in TDP-43Δ208–414-expressing astrocytes (37.5% RFP-TDP-43wt versus 31.2% RFP-TDP-43Δ208–414; Table 2, Fig. 7A). These results suggest a downregulation of MCT1 transporters in astrocytes with TDP-3R208–414 mutant pDNA construct, which indicates a decreased astroglial lactate release capacity.

### Table 2. Responsiveness of astrocytes transfected with RFP-tagged TDP-43 pDNA constructs to noradrenaline- and isoprenaline-induced changes in intracellular cAMP and lactate levels. 

| Experimental group | FRET nanosensor | α (%) increase | β (%) decrease | n all |
|--------------------|----------------|---------------|----------------|------|
|                    | RFP-TDP-43wt   | 9 (100)       | 0 (0)          | 9    |
|                    | RFP-TDP-43Δ208–414 | 9 (100)       | 0 (0)          | 9    |
| Epac1-camps        | RFP-TDP-43wt   | 9 (42.0)      | 4 (4.0)        | 26   |
|                    | RFP-TDP-43Δ208–414 | 7 (70.0)       | 3 (30.0)        | 10   |
| Laconic            | RFP-TDP-43wt   | 16 (64.0)     | 0 (0)          | 25   |
|                    | RFP-TDP-43Δ208–414 | 9 (60.0)     | 6 (40.0)        | 15   |
| Isoprenaline       | RFP-TDP-43wt   | 9 (100)       | 0 (0)          | 25   |
|                    | RFP-TDP-43Δ208–414 | 7 (70.0)       | 3 (30.0)        | 10   |

*P* = 0.03. The results revealed that the amplitudes (ΔFRET [%]) and the initial rates of the Laconic FRET signal increase (ΔFRET/Δtime [%/min]) in NA-responsive cells were similar in the RFP-TDP-43wt- and the RFP-TDP-43Δ208–414-expressing astrocytes (3.2 ± 0.5% [RFP-TDP-43wt; n = 9] versus 3.1 ± 0.4% [RFP-TDP-43Δ208–414; n = 7; P = 0.83] and 1.5 ± 0.4%/min [RFP-TDP-43wt; n = 9] versus 1.7 ± 0.6%/min [RFP-TDP-43Δ208–414; n = 7; P = 0.77]; respectively; Fig. 5A, Table 2). In control experiments, in which isolated astrocytes were transfected with Laconic only (no co-transfection with RFP-TDP-43 constructs), stimulation with NA (100 µM) elicited similar increases in [lactate], as in astrocytes expressing RFP-TDP-43wt (Online resource 1, Fig. S2B; n = 7 cells), indicating that overexpression of RFP-TDP-43wt does not affect the normal glycolytic response in astrocytes. However, when we looked at the whole population of astrocytes, we observed that the responsiveness of astrocytes to NA-induced lactate production increased by 1.6-fold (from 42.8% to 70.0%) in cells expressing RFP-TDP-43Δ208–414 compared with astrocytes expressing RFP-TDP-43wt (Fig. 5C; Table 2), suggesting that the probability of activating aerobic glycolysis in a cell population is facilitated in astrocytes with TDP-3R208–414 cytoplasmic inclusions. In control astrocytes expressing only Laconic (no co-transfection with RFP-TDP-43 constructs), the responsiveness of astrocytes to NA-induced lactate production was similar to that in astrocytes expressing RFP-TDP-43wt (31.8% versus 42.8%, respectively).

When we treated astrocytes with the selective β2-AR agonist Iso, the responsiveness of cells was similar (64.0% [RFP-TDP-43wt] versus 60.0% [RFP-TDP-43Δ208–414]; Table 2, Fig. 5D). The mean amplitude and the initial rate of the Laconic FRET signal increase were 1.6-fold and 2-fold lower, respectively, but statistically insignificantly different, in the RFP-TDP-43Δ208–414 than in the RFP-TDP-43wt-expressing astrocytes (2.6 ± 0.5% [RFP-TDP-43wt; n = 16] versus 1.6 ± 0.2% [RFP-TDP-43Δ208–414; n = 9; P = 0.2] and 2.2 ± 1.2%/min [RFP-TDP-43wt; n = 16] versus 1.1 ± 0.1%/min [RFP-TDP-43Δ208–414; n = 9; P = 0.4]; respectively; Fig. 5B, Table 2).

The expression of MCT1 transporters is reduced in TDP-43Δ208–414-expressing astrocytes. Since NA-mediated lactate production was enhanced in astrocytes with TDP-43 inclusions (Fig. 5), which may affect the availability of extracellular lactate, we next investigated whether the presence of TDP-43 inclusions alters the expression level of astrocyte-specific monocarboxylate transporters (MCT), which are in astrocytes predominantly responsible for L-lactate transport across the plasma membrane. We immunostained astrocytes expressing RFP-TDP-43wt and RFP-TDP-43Δ208–414 with antibodies against MCT1 and MCT4 transporters (Fig. 7). The expression level of MCT4 transporters did not significantly differ between the RFP-TDP-43wt- and RFP-TDP-43Δ208–414-expressing astrocytes (7.8% ± 0.9% [n = 47] versus 6.4% ± 0.8% [n = 42; P = 0.25]; Fig. 7B), while the expression of MCT1 transporters was significantly lower in astrocytes expressing RFP-TDP-43Δ208–414 (4.2% ± 0.5% [n = 45] versus 2.7% ± 0.5% [n = 47; P < 0.01]; Fig. 7A). These results suggest a downregulation of MCT1 transporters in astrocytes with ALS- and FTD-U-linked TDP-43 inclusions, which indicates a decreased astroglial lactate release capacity.
Figure 5. Noradrenaline- and isoprenaline-induced increase in [lactate]i in astrocytes expressing RFP-TDP-43<sup>208–414</sup> versus RFP-TDP-43<sup>wt</sup>. (A, B) panels i Representative (left) and average (right) time-dependent changes in the Laconic FRET signal increase (∆FRET; mTFP/Venus) after the addition of 100 µM NA (A,i) and 100 µM Iso (B,i; black lines) in astrocytes co-expressing RFP-TDP-43<sup>wt</sup> (black line/circles; n = 9 (NA), n = 16 (Iso)) or RFP-TDP-43<sup>208–414</sup> (grey line/circles; n = 7 (NA), n = 9 (Iso)). Data are expressed as percentages of the inverse FRET signal (mTFP/Venus), denoting an increase in [lactate], relative to the baseline FRET signal. Each data point in the right panel represents the mean ± SEM. (A, B) panels ii, iii Mean changes in the Laconic FRET signal increase (Mean ∆FRET; (A, B) panels ii) and the mean initial rates of the FRET signal increase (∆FRET/Δt; (A, B) panels iii) after the addition of NA (A) and Iso (B) for RFP-TDP-43<sup>wt</sup> and RFP-TDP-43<sup>208–414</sup> experimental groups. Numbers adjacent to the error bars depict the number of cells analysed. Data are presented as means ± SEM and acquired from at least two different animals (one cell was recorded per coverslip). The Student’s t-test, used to test significant differences between astrocytes expressing RFP-TDP-43<sup>208–414</sup> and RFP-TDP-43<sup>wt</sup>, revealed the similarity of the responses, however, in Iso-treated astrocytes expressing RFP-TDP-43<sup>208–414</sup> there was a trend towards the reduction in the [lactate]i increase. (C, D) Pie graphs showing the responsiveness of astrocytes to (C) noradrenaline- and (D) isoprenaline-induced changes in intracellular lactate levels. Note that the probability of observing a response to NA with production of lactate in RFP-TDP-43<sup>208–414</sup>-expressing astrocytes was 1.6-fold higher compared to RFP-TDP-43<sup>wt</sup>-expressing astrocytes, but not in Iso-treated cells (see also Table 2).
Figure 6. Reduced expression of β2-adrenergic receptors in RFP-TDP-43<sup>208–414</sup> compared with RFP-TDP-43<sup>wt</sup>-expressing astrocytes. (A–C) Representative fluorescence images of astrocytes immunostained with α<sub>1</sub>- (A) β<sub>1</sub>- (B) and β<sub>2</sub>-adrenergic receptor (C) antibodies (green) and labelled with DAPI (blue) in RFP-TDP-43<sup>wt</sup>- (upper panels) and RFP-TDP-43<sup>208–414</sup>-expressing astrocytes (lower panels; red). Immunostaining was performed 30 h after transfection with RFP-tagged TDP-43 pDNA constructs. Scale bar, 20 µm. Histograms show anti-α<sub>1</sub>- (A) anti-β<sub>1</sub>- (B) and anti-β<sub>2</sub>-adrenergic receptor (AR; C) positive cell cross-sectional area (anti-α<sub>1</sub>-/β<sub>1</sub>-/β<sub>2</sub>-AR S; i.e. number of green fluorescence pixels with fluorescence intensity above the threshold of 10% of maximal fluorescence) per total cell cross-sectional area (cell S; i.e. number of all pixels) in RFP-TDP-43<sup>wt</sup>- and RFP-TDP-43<sup>208–414</sup>-expressing cells. Note the reduced expression of β2-adrenergic receptors in RFP-TDP-43<sup>208–414</sup>- compared with RFP-TDP-43<sup>wt</sup>-expressing astrocytes. Numbers adjacent to the error bars depict the number of cells analysed. Data are presented as means ± SEM and acquired from at least two different animals. Each experiment (i.e. coverslip) was performed in duplicate, multiple cells were recorded per coverslip. ***P ≤ 0.001, Mann-Whitney U test.
Discussion

Based on the new disease models, a number of recent studies have highlighted the involvement of non-neuronal cells in the pathogenesis of ALS and FTD-U, including astrocytes, which provide metabolic and trophic support to motor neurons. However, the molecular mechanisms of astroglial-mediated neurotoxicity in ALS and FTD-U remain poorly understood. Here, we investigated whether astroglial expression of the C-terminal fragment of TDP-43 (TDP-43\textsuperscript{208–414}), a major component of ALS- and FTD-U-associated pathologic cytoplasmic inclusions, affects astroglial cell metabolism.

Expression of C-terminal fragment of TDP-43 in isolated cortical rat astrocytes has led to the formation of cytoplasmic TDP-43 inclusions, which can mimic key biochemical features of TDP-43 proteinopathies, consistent with studies in other cell types. Astrocytes with cytoplasmic TDP-43 inclusions had a 3-fold lower amount of endogenous nuclear TDP-43 (which may cause a partial loss-of-function of nuclear TDP-43) compared with astrocytes expressing WT TDP-43, where most of the TDP-43 was present in the cell nucleus. This indicates that expression of the C-terminal fragment of TDP-43 in astrocytes affects trafficking of endogenous TDP-43 between the nucleus and the cytoplasm, consistent with reports on neurons, glial cells from human tissue samples, various cell lines (e.g. QBI-293 and tsBN2 cells), and muscle cells. The results suggest that aggregated TDP-43 prevents newly synthesized endogenous TDP-43 from being imported into the nucleus and/or inhibits the re-entry of existing cytoplasmic TDP-43 into the nucleus. Interestingly, the transfection with inclusion-forming TDP-43, caused in neighboring non-transfected astrocytes (with no visible RFP signal) a small,

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**Figure 7.** Reduced expression of MCT1 transporters in RFP-TDP-43\textsuperscript{208–414} compared with RFP-TDP-43\textsuperscript{wt}. Representative fluorescence images of astrocytes immunostained with antibodies against MCT1 (A) and MCT4 transporters (B, green) and labelled with DAPI (blue) in RFP-TDP-43\textsuperscript{wt} (upper panels) and RFP-TDP-43\textsuperscript{208–414} expressing astrocytes (lower panels; red). Immunostaining was performed 24 h after transfection with RFP-tagged TDP-43 pDNA constructs. Scale bar, 10 \( \mu \text{m} \). Histograms show anti-MCT1 (A) and anti-MCT4 (B) positive cell cross-sectional area (anti-MCT1/MCT4 \( S \); i.e. number of green fluorescence pixels with fluorescence intensity above the threshold of 20% of maximal fluorescence) per total cell cross-sectional area (cell \( S \); i.e. number of all pixels) in RFP-TDP-43\textsuperscript{wt} and RFP-TDP-43\textsuperscript{208–414}-expressing cells. Note the reduced expression of MCT1 transporters in RFP-TDP-43\textsuperscript{208–414} compared with RFP-TDP-43\textsuperscript{wt}-expressing astrocytes. Numbers adjacent to the error bars depict the number of cells analysed. Data are presented as means ± SEM and acquired from four different animals. Each experiment (i.e. coverslip) was performed in duplicate, multiple cells were recorded per coverslip. **\( P \leq 0.01 \), Mann-Whitney U test.
albeit not significant, trend in reduced percentage of DAPI and TDP-43-colabeled nuclei, which suggests that the transfection with the C-terminal fragment of TDP-43 might affect the physiology of non-transfected cells. In pathological conditions, mimicked here by the expression of inclusion-forming TDP-43, astrocytes bear a significant functional plasticity, known as reactive astroglia66. These astrocytes secret or distribute through gap junctions various cytotoxic factors, such as Lcn212, interleukin-6, ciliary neurotrophic factor, etc.98, which can affect neighboring cells. Even though we did not specifically test whether astrocytes expressing inclusion-forming TDP-43 transform into a reactive phenotype, this outcome is possible. If this is the case, the observed reduction in the nuclear TDP-43 staining in some non-transfected astrocytes adjacent to inclusion-forming TDP-43 astrocytes may be a consequence of altered physiological state of these cells affecting the TDP-43 gene expression level or the synthesis/degradation/distribution of TDP-43.

Because TDP-43 is involved in multiple aspects of RNA processing, any changes in TDP-43 nuclear level may have detrimental effects on astroglial physiology4, including on cell metabolism. LD accumulation has been observed in glial cells, including astrocytes, in early stages of neurodegeneration96. Recently, alterations in lipid metabolism (accumulation of cholesteryl esters, determined with lipidomic analysis) in spinal cords from SOD1159α transgenic mouse model have been reported that might be linked to astrogliosis and LD formation in astrocytes68, since a population of astrocytes isolated from the degenerating spinal cords of the same animal model exhibited significant abundance of LDs as well as autophagic and secretory vesicles, all characteristic features of cellular stress and inflammatory activation96. However, the mechanisms leading to increased LD accumulation in astrocytes are poorly understood and may, among others, rely on altered neuronal mitochondrial function and ROS as well as on astrocyte-neuron lactate shuttle101, in particular on astroglial lactate-derived lipid production in neurons and transfer of excess lipids in lipoprotein-like particles (ApoE) from neurons to astrocytes102,103. We show here that in astrocytes with TDP-43 inclusions the LD present in enhanced (the size and the number of LDs) in the absence of neighboring neurons, suggesting the existence of an alternative astroglial-mediated mechanism triggering accumulation of LDs through altering the balance between biogenesis and degradation of LDs. Accumulation of LDs in astrocytes with cytoplasmic TDP-43 inclusions may be a response to cellular inflammation, which is typically found in the pathology of various neurologic disorders, including ALS68.2. Here, LDs are hypothesized to be an important source of energy for proliferation and may serve a protective role by gathering free fatty acids to protect cells against lipotoxicity93.

Besides alterations in LD metabolism, changes in noradrenergic regulation of glucose metabolism were observed in astrocytes with cytoplasmic TDP-43 inclusions. Astrocytes with TDP-43 inclusions exhibited down-regulation of β2-ARs and a 35% reduction in NA-mediated increase in [cAMP]1. Consistent with our results, dysregulation of astrocytic β2-AR/cAMP signalling has been suspected to contribute to the pathology of a number of other neurologic disorders, including multiple sclerosis, Alzheimer’s disease, human immunodeficiency virus encephalitis, and others94. Reduction of β2-AR expression was reported in human white matter astrocytes obtained from post mortem brain tissue of patients with multiple sclerosis95. Moreover, it was demonstrated both in vitro and in vivo that the presence of Alzheimer’s disease associated amyloid beta peptide (Aβ) in prefrontal cortical neurons leads to internalization and degradation of β2-ARs, which leads to subsequent attenuation of cAMP signalling96. Since aerobic glycolysis in astrocytes is upregulated with β2-AR/cAMP signaling, one would expect that astrocytes with TDP-43 inclusions and a reduced expression of β2-ARs will exhibit reduced β2-adrenergic mediated aerobic glycolysis and lactate production. When we stimulated astrocytes with Iso, a selective β2-agonist, although the responsiveness of cells to Iso was unchanged, there was a trend in reduction of [lactate] increase, since the amplitude in [lactate] increase was ~2-fold lower (P = 0.08) in astrocytes with TDP-43 inclusions, consistent with downregulation of β2-AR and cAMP signaling in these cells. In contrast to Iso stimulation, the amplitude and the rate of [lactate] increase upon NA stimulation was unaltered in astrocytes with TDP-43 inclusions, but the probability of activating aerobic glycolysis, measured as increased responsiveness to NA, was increased by 1.6-fold in astrocytes with TDP-43 inclusions. When viewing the astroglial population as a whole, this means that glycolytic lactate production upon NA stimulation is facilitated in astrocytes with TDP-43 inclusions.

Besides cAMP, Ca2+ signals through activation of α2-AR/Gαq-protein signaling pathway have important role in regulation of NA-mediated glucose metabolism in astrocytes38. Abnormal Ca2+ homeostasis has been observed in astrocytes isolated from SOD1159α animals. In particular, excess Ca2+ release from ER stores upon purinergic/Gq-protein signaling pathway activation has been reported due to abnormal ER Ca2+ accumulation96. If such a mechanism exists in astrocytes with TDP-43 inclusions, binding of NA to α2-AR may lead to excess Ca2+ release from ER and enhanced aerobic glycolysis despite downregulation of β2-AR/cAMP signaling pathway. However, contrary to the results obtained on SOD1159α animal model, we observed a 31% reduction in Ca2+ signaling in astrocytes with TDP-43 inclusions, even though the level of α2-AR expression was unchanged. It has been reported that β2-AR/cAMP and α3-AR/Ca2+ signaling pathways interact in astrocytes, enhancing each other97, therefore downregulation of β2-ARs or α3-ARs may reduce the noradrenergic Ca2+ response via α2-ARs, explaining the reduction of both noradrenergic cAMP and Ca2+ signals despite an unaltered expression of α2-ARs.

It has been reported that morphologic changes in astrocytes exhibit a bell-shaped dependency on [cAMP]37. If aerobic glycolysis in astrocytes displays a similar bell-shaped dependency on [cAMP], astrocytes with reduced β2-AR/cAMP signalling may actually attain enhanced metabolic responsiveness to noradrenergic stimulation. Moreover, perturbances in TDP-43 can change the transcriptome and proteome of a cell affecting the expression level of enzymes involved in LD metabolism and aerobic glycolysis, as was observed in other cell types with a TDP-43 knock down86. Whether expression level of metabolic enzymes is altered in astrocytes with TDP-43 inclusions and whether this contributes to the observed enhanced astroglial metabolism needs to be investigated in the future.

Increased lactate production upon NA stimulation in astrocytes with TDP-43 inclusions may lead to a better metabolic support of neurons with lactate due to lactate flux generated between astrocytes and neurons77. This
is, however, contradictory to the CNS hypometabolism observed in patients with neurodegenerative diseases, including ALS. Recently, decreased expression of lactate MCT1 and MCT4 transporters has been reported post mortem in the motor cortex of ALS patients compared to non-ALS patients. Moreover, downregulation of MCT1 mRNA in the spinal cords of early symptomatic and endstage SOD1 transgenic mice model of ALS has been observed, presumably in glia (oligodendrocytes and astrocytes). Down-regulation of the lactate MCT4 transporter has been also demonstrated in spinal cord astrocytes from patients with ALS with SOD1 mutations and in pre-symptomatic SOD1 transgenic mice. We show here that expression of C-terminal fragment of TDP-43 (TDP-43) in the nucleus, possibly due to downregulation of β2-adrenergic receptor (β2-AR). In these cells aerobic glycolysis and lipid droplet (LD) accumulation are facilitated representing cellular stress. Moreover, monokarboxylate transporter 1 (MCT1) is downregulated in astrocytes with TDP-43 inclusions, suggesting that despite increased astroglial aerobic glycolysis astroglial L-lactate support of neurons may be reduced in ALS or FTD-U. ALS, amyotrophic lateral sclerosis; ER, endoplasmic reticulum; FTD, frontotemporal dementia with ubiquitin-positive inclusions (FTD-U); TDP-43, TAR DNA-binding protein 43.

In conclusion, the results of the present study show that expression of the C-terminal fragment of TDP-43 in isolated rat cortical astrocytes leads to the formation of TDP-43-positive cytoplasmic inclusions, a hallmark of ALS. These astrocytes exhibit reduced NA-mediated cAMP and Ca2+ signaling, whereas both aerobic glycolysis and LD presence appear facilitated. Although NA-mediated L-lactate production was increased in astrocytes with TDP-43 inclusions, the expression of lactate MCT1 transporters was reduced, suggesting decreased astroglial lactate release capacity (Fig. 8). Thus, these findings reflect an astroglial stressed state that may fail to adequately metabolically support neurons in ALS and FTD-U, leading to neurotoxicity.

Methods

Cell culture and transfection. Unless noted otherwise, all chemicals were of the highest quality available and purchased from Sigma-Aldrich (Merck KGaA, Darmstadt, Germany).

Primary astrocyte cultures were prepared from the cerebral cortices of 2- to 3-day-old Wistar rats, as described previously, and grown in high-glucose Dulbecco’s modified Eagle’s medium supplemented with 10% fetal bovine serum, 1 mM sodium pyruvate, 2 mM l-glutamine and 25 µg/ml penicillin-streptomycin in a vaporized atmosphere containing 95% air and 5% CO2 at 37 °C until reaching 70%–80% confluence. Confluent cultures were shaken overnight at 225 rpm and the medium was changed the next morning; this was repeated three times. After the third overnight shaking, the cells were trypsinized and put in flat tissue culture tubes with 10 cm2 growth area. After reaching confluence again, the cells were subcultured onto 22-mm diameter poly-l-lysine-coated glass coverslips. This procedure yielded astrocytes with > 95% purity, determined by anti-glial fibrillary acidic protein (GFAP) antibody staining.

After 1–3 days, astrocytes were co-transfected with the genetically encoded FRET-based cAMP nanosensor Epac1-camps or lactate nanosensor Lacomic and RFP-tagged WT TDP-43 (pTagRFP-C::TDP-43) or RFP-tagged C-terminal fragment of TDP-43 (pTagRFP-C::TDP-43) using FuGENE 6 Transfection Reagent (Promega Corporation, Madison, WI, USA). Transfection medium contained no serum or antibiotics.

The experimental animals were cared for in accordance with the International Guiding Principles for Biomedical Research Involving Animals developed by the Council for International Organizations of Medical
ing RFP-TDP-43wt or RFP-TDP-43208–414 were fixed with 4% formaldehyde in phosphate buffered saline (PBS) for 15 min and then permeabilized with 0.1% Triton X-100 for 10 min at room temperature (except for MCT1 and MCT4) before being treated with 10% goat serum for 1 h at 37 °C. Astrocytes were then stained with primary antibodies against endogenous TDP-43 (C-terminal, rabbit polyclonal, 1:400; Proteintech, Manchester, UK), α1-AR (rabbit polyclonal, 1:100; Abcam, Cambridge, UK), β1-AR (rabbit polyclonal, 1:200; Abcam, Cambridge, UK), β2-AR (rabbit polyclonal, 1:100; Biovendor, Cambridge, UK), MCT1 (rabbit polyclonal, 1:50; Abcam, Cambridge, UK) and MCT4 (rabbit polyclonal, 1:50; Santa Cruz, Texas, US) overnight at 4 °C. After washing with PBS, cells were incubated for 1 h at 37 °C with Alexa Fluor 488-conjugated secondary goat anti-rabbit IgG (1:600; Abcam, Cambridge, UK). Excess antibodies were washed off and the coverslips were mounted onto glass slides using SlowFade antifade reagent with DAPI (Molecular Probes by Life Technologies, Thermo Fisher Scientific, Massachusetts, USA) and carefully sealed. Immunolabelled cells were imaged with an inverted Zeiss LSM780 confocal microscope with a Plan apochromatic 40×1.4 oil immersion objective (Carl Zeiss, Jena, Germany) using 488-nm Ar-ion, 543-nm He-Ne and 405-nm diode laser excitation. Emission spectra were acquired sequentially with 505- to 530-nm bandpass (Alexa Fluor488), 560-nm long pass (TagRFP414) and 445- to 450-nm bandpass (DAPI) emission filters.

Colocalization analysis of Alexa Fluor488 (immunolabelled TDP-43), TagRFP584 (RFP-TDP-43 pDNA constructs), and DAPI fluorescence signals was performed on exported TIFF files using ColocAna software (Celica Biomedical, Ljubljana, Slovenia) that counts all red, green, blue and colocalized (green and red or green and blue) pixels within the image. The threshold for the colocalized pixel count was set at 20% of the maximal green, red or blue fluorescence intensity, respectively. Colocalization was expressed as the ratio of colocalized to green or blue pixels (as percentages). Kruskal-Wallis one-way analysis of variance (ANOVA) on ranks (followed by Dunn's test) or Mann-Whitney U test were performed to determine statistical significance between the experimental groups. P < 0.05 was considered significant.

To determine the expression level of different ARs and MCTs, the number of α1-AR-, β1-AR-, β2-AR-, MCT1- and MCT4-positive green fluorescence pixels with fluorescence intensity above the threshold of 10% (α1-/β1-/β2-AR-positive cell area) or 20% (MCT1 and MCT4-positive cell area) of maximal fluorescence and the number of all pixels (total cell area) per cell cross-sectional area were determined for each cell separately in RFP-TDP-43wt- and RFP-TDP-43208–414-expressing astrocytes using ZEN software (Zeiss, Oberkochen, Germany). The percentage of the AR- and MCT-positive cell area relative to the total cell area was calculated for RFP-TDP-43wt- and RFP-TDP-43208–414-expressing astrocytes for individual receptor and transporter type. The Mann-Whitney U test was performed to determine statistical significance between the experimental groups. P < 0.05 was considered significant.

To determine the extent of DAPI and TDP-43-colabeled nuclei in non-transfected astrocytes (with no visible RFP signal) adjacent to the RFP-TDP-43wt- and RFP-TDP-43208–414-expressing astrocytes (with visible RFP signal) we measured the percentage of DAPI and TDP-43-colabeled nuclei per all DAPI nuclei in neighboring non-transfected cells (with no visible RFP signal) in the RFP-TDP-43wt and RFP-TDP-43208–414 experimental groups. In the control non-transfected group, we analyzed the nuclei of all cells. Some partially visible DAPI-stained nuclei at the edges of the confocal images were also taken into account in the analysis, however, only if no RFP signal in or around the visible part of the nuclei was observed. Kruskal-Wallis one-way ANOVA on ranks, followed by Dunn's test was performed to determine statistical significance between the experimental groups. P < 0.05 was considered significant.

**Lipid droplet staining and data analysis.** Control (non-transfected) astrocytes and astrocytes transfected with RFP-TDP-43wt or RFP-TDP-43208–414 plasmid were incubated in fresh growth medium for 24 h. Cells were then fixed in 4% formaldehyde in PBS for 5 min and stained with 1 μg/ml BODIPY493/503 (Molecular Probes by Life Technologies, Thermo Fisher Scientific, Massachusetts, USA), a fluorescent LD marker, for 6 min at room temperature. Excess dye was washed off and the coverslips were mounted onto glass slides using SlowFade antifade reagent with DAPI (Molecular Probes by Life Technologies, Thermo Fisher Scientific, Massachusetts, USA) and carefully sealed. Stained cells were imaged with an inverted Zeiss LSM780 confocal microscope with a Plan apochromatic 40×1.4 oil immersion objective (Carl Zeiss, Jena, Germany) using 488-nm Ar-ion, 543-nm He-Ne and 405-nm diode laser excitation. Emission spectra were acquired sequentially with 505- to 530-nm bandpass (BODIPY493/503), 560-nm long pass (TagRFP414) and 445- to 450-nm bandpass (DAPI) emission filters.

To determine the LD content in individual astrocytes, the number of BODIPY493/503-positive green fluorescence pixels with fluorescence intensity above the threshold of 20% of maximal fluorescence (Lipid droplet S) and the number of all pixels (Cell S) were determined for each cell separately in control, RFP-TDP-43wt- and RFP-TDP-43208–414-expressing astrocytes in ZEN software (Zeiss, Oberkochen, Germany). The values obtained were normalized to the average LD content in control non-transfected cells. The mean number of BODIPY493/503-labeled LDs per cell and the mean LD perimeter were determined in cross-sections of individual cells using ImageJ. Analyze Particles function after applying 20% threshold and signal intensity (watershed) segmentation on individual images. Then, assuming that all LDs are spherical, the mean LD diameter was
estimated from the perimeter values with the equation \( d = C/\pi \), where \( d \) is the diameter and \( C \) is the LD perimeter. Kruskal–Wallis one-way ANOVA on ranks, followed by Dunn’s test was performed to determine statistical significance between the groups. \( P < 0.05 \) was considered significant.

**FRET measurements of intracellular cAMP and lactate levels and data analysis.** Cells co-expressing the FRET-based nanosensor Epac1-camps or Laconic and RFP-tagged TDP-43 pDNA construct (RFP-TDP-43wt or RFP-TDP-43208–414) were examined 24–30 h after transfection with a fluorescence microscope (Zeiss Axio Observer.A1 (Zeiss, Oberkochen, Germany), with a CCD camera and monochromator Polychromy V (Till Photonics, Graefelfing, Germany) as a monochromatic source of light with a wavelength 436 nm/10 nm. Dual emission intensity ratios were recorded using an image splitter (Optical Insights, Tucson, AZ, USA) and two emission filters (465/30 nm for CFP [cyan fluorescent protein] or mTFP [monomeric teal fluorescent protein] and 535/30 nm for YFP [yellow fluorescent protein] or Venus). Images were acquired every 3.5 s for Epac1-camps and 10 s for Laconic. Exposure time was 100 ms.

In some experiments astrocytes co-expressing Laconic and RFP-TDP-43wt or RFP-TDP-43208–414 were examined 24 h after transfection with a fluorescence microscope (Zeiss Axio Observer.A1 (Zeiss, Oberkochen, Germany)) with a Axiocam 702 camera and Colibri.2 Lamp Module (Zeiss, Oberkochen, Germany) as a source of light with a wavelength 433 nm. Dual emission intensity ratios were recorded using an image splitter (Optical Insights, Tucson, AZ, USA) and two emission filters (469–491 nm for ECFP and 530–4095 nm for EYFP). Images were acquired at intervals of 10 s with exposure time of 100 ms.

Coverslips with transfected astrocytes were mounted in a superfusion recording chamber on the microscope stage. Imaging was performed at room temperature (22–24 °C). One cell per experiment was recorded. The FRET signals (CFP/YFP (Epac1-camps) and mTFP/Venus (Laconic) signals) were obtained from the integration of the ratio signal over the entire cell using Life Acquisition software (Till Photonics, Graefelfing, Germany) or ZEN (Carl Zeiss, Jena, Germany). In the graphs, the FRET signal was reported as the ratio of the CFP/YFP (Epac1-camps) and mTFP/Venus (Laconic) fluorescence signals after subtracting the background fluorescence from the individual fluorescence signals using Excel (Microsoft, Seattle, WA, USA). The values of the FRET ratio signals were normalized to 1.0. An increase in the FRET ratio signal reflects an increase in [cAMP] or [lactate].

Before the experiments, astrocytes were kept in extracellular solution containing sodium bicarbonate for 10 min (10 mM Hepes/NaOH [pH 7.2], 3 mM d-glucose, 135.3 mM NaCl, 1.8 mM CaCl2, 2 mM MgCl2, and 5 mM KCl, 0.5 mM NaH2PO4·H2O, 5 mM NaHCO3), and then treated with 100 µM NA (non-selective AR agonist) or 100 µM Iso (selective β-AR agonist) following a 100- to 200-s baseline. Experiments were conducted with the addition of a bolus solution; 200 µl of extracellular solution containing NA was added by pipette to 200 µl of bath solution in the recording chamber. The application of a control bolus solution without reagents had no significant effect on the FRET signal, as reported previously82,83. Extracellular solution osmolality was 295–305 mOsm, measured with the Osmomat 030 freezing point osmometer (Gonotec GmbH, Germany).

In experiments with Epac1-camps, single-exponential increases to maximum functions \( F = F_0 + c \times (1 - \exp(-t/\tau)) \) were fitted to the FRET ratio signals using SigmaPlot. The time constant (\( \tau \)) and amplitude changes in the FRET ratio signal \( (\Delta FRET [\%]) \) were determined from the fitted curves. \( F \) is the FRET ratio signal at time \( t \), \( F_0 \) is the baseline FRET ratio signal, \( c \) is the FRET ratio signal amplitude of \( F - F_0 \), and \( \tau \) is the time constant of the individual exponential component. In experiments with Laconic, the maximal (initial) rates of the FRET ratio signal increase \( (\Delta FRET/\Delta t) \) were calculated as the slope of the linear regression function \( (\Delta FRET [\%] = \text{slope} [\%/min] \times \Delta t [\text{min}]) \) fitting the initial FRET ratio signal increase. In these experiments, changes in the FRET ratio signal \( (\Delta FRET [\%]) \) were calculated by subtracting the mean maximal FRET ratio signals from the mean baseline FRET ratio signals.

Unless stated otherwise, the Student’s t-test was performed to determine statistical significance between the experimental groups; \( P < 0.05 \) was considered significant.

**Fluo-4 AM measurements of cytosolic Ca2+ and data analysis.** Astrocytes expressing RFP-TDP-43wt or RFP-TDP-43208–414 were incubated for 30 min at room temperature in medium containing 2 µM Fluo-4 AM dye (Molecular Probes, Invitrogen) and then transferred to dye-free medium for at least 30 min before the experiments to allow for cleavage of the AM ester group. The cells were excited with an Argon-ion laser at 488 nm, and time-lapse images were obtained every 3 s with an inverted Zeiss LSM780 confocal microscope and an 20x objective. Emission light was acquired with a 505–530-nm band-pass emission filter. Fluo-4 AM-labeled astrocytes were after 100 s baseline stimulated with 100 µM NA. Total recording time was ~400 s (135 frames). In individual cells, Fluo-4 AM intensity was quantified within a region of interest and expressed as the relative change in fluorescence: \( \Delta F/F_0 = (F - F_0)/F_0 \), where \( F_0 \) denotes the baseline fluorescence level after subtraction of background fluorescence. The peak and cumulative increase in Fluo-4 AM \( \Delta F/F_0 \) were determined using Microsoft Excel.

Mann-Whitney U test was performed to determine statistical significance between the experimental groups. \( P < 0.05 \) was considered significant.

**Data availability**
All data generated or analyzed during this study are included in this published article and its Supplementary Information files or are available from the corresponding author on reasonable request.

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References

1. Hardiman, O. et al. Amyotrophic lateral sclerosis. Nature reviews. Disease primers 3, 17071, https://doi.org/10.1038/nrdp.2017.71 (2017).
2. Peters, O. M., Ghasemi, M. & Brown, R. H. Jr. Emerging mechanisms of molecular pathology in ALS. J. Clin. Invest. 125, 1767–1779, https://doi.org/10.1172/JCI71601 (2015).
3. Lee, E. B., Lee, Y. M. & Trojanowski, J. Q. Gains or losses: molecular mechanisms of TDP43-mediated neurodegeneration. Nat. Rev. Neurosci. 13, 38–50, https://doi.org/10.1038/nrn3121 (2011).
4. Radford, R. A. et al. The established and emerging roles of astrocytes and microglia in amyotrophic lateral sclerosis and frontotemporal dementia. Front. Cell. Neurosci. 9, 414, https://doi.org/10.3389/fncel.2015.00414 (2015).
5. Neumann, M. et al. Ubiquitin-driven TDP-43 in frontotemporal lobar degeneration and amyotrophic lateral sclerosis. Science 314, 130–133, https://doi.org/10.1126/science.1134108 (2006).
6. Arai, T. et al. TDP-43 is a component of ubiquitin-positive tau-negative inclusions in frontotemporal lobar degeneration and amyotrophic lateral sclerosis. Biochem Biophys Res Commun 351, 602–611, https://doi.org/10.1016/j.bbrc.2006.09.033 (2006).
7. Sloan, S. A. & Barres, B. A. Glia as primary drivers of neuropathology in TDP-43 proteinopathies. Proc. Natl. Acad. Sci. USA 110, 4439–4440, https://doi.org/10.1073/pnas.1106188110 (2013).
8. Chen-Plotkin, A. S., Lee, V. M. & Trojanowski, J. Q. TAR DNA-binding protein 43 in neurodegenerative disease. Nat. Rev. Neurol. 6, 211–220, https://doi.org/10.1038/nrneurol.2010.18 (2010).
9. Sreedharan, J. et al. TDP-43 mutations in familial and sporadic amyotrophic lateral sclerosis. Science 319, 1668–1672, https://doi.org/10.1126/science.1154584 (2008).
10. Winton, M. J. et al. Disturbance of nuclear and cytoplasmic TAR DNA-binding protein (TDP-43) induces disease-like redistribution, sequestration, and aggregate formation. J. Biol. Chem. 283, 13302–13309, https://doi.org/10.1074/jbc.M800342200 (2008).
11. Smelakhtur, P., Sidle, K. C. & Hardy, J. Review: Prion-like mechanisms of transactive response DNA binding protein of 43 kDa (TDP-43) in amyotrophic lateral sclerosis (ALS). Neurophysiol. Appl. Neurobiol. 41, 578–597, https://doi.org/10.1011/nn.12006 (2015).
12. Aoki, C. Beta-adrenergic receptors: astrocytic localization in the adult visual cortex and their relation to catecholamine axon terminals as revealed by electron microscopic immunocytochemistry. J Neurosci 12, 781–792 (1992).
13. Scotter, E. L. et al. Differential roles of the ubiquitin proteasome system and autophagy in the clearance of soluble and aggregated TDP-43 species. J Cell Sci 127, 1263–1278, https://doi.org/10.1242/jcs.140087 (2014).
14. Zorec, R., Parpura, V. & Verkhratsky, A. Preventing neurodegeneration by adrenergic astroglial excitation. FEBS J., https://doi.org/10.1111/febs.14456 (2018).
15. Müller, M. S., Fouyssac, M. & Taylor, C. W. Effective Glucose Uptake by Human Astrocytes Requires Its Sequestration in the Intracellular Glucose Pool. J Neurochem, 284, 8516–8524, https://doi.org/10.1111/jn.13825 (2009).
16. Vardjan, N. & Zorec, R. Excitable Astrocytes: Ca(2 +)- and cAMP-Regulated Exocytosis. J. Biol. Chem. 288, 3481–3486.e3484, https://doi.org/10.1074/jbc.C113.500272 (2013).
17. Horvat, A. & Vardjan, N. Astroglial cAMP signalling in space and time. Neurosci Lett. 672, 170–177, https://doi.org/10.1016/j.neulet.2018.02.025 (2018).
18. Horvat, A., Zorec, R. & Vardjan, N. Adrenergic stimulation of single rat astrocytes results in distinct temporal changes in intracellular Ca(2 +) and cAMP-dependent PKA responses. Cell Calcium 59, 156–163 (2016).
40. O’Donnell, J., Zeppenfeld, D., McConnell, E., Penia, S. & Nedergaard, M. Norepinephrine: a neuromodulator that boosts the function of multiple cell types to optimize CNS performance. *Neurochem. Res.* 37, 2496–2512, https://doi.org/10.1007/s11064-012-0818-x (2012).

41. Magistretti, P. J. & Allaman, I. A cellular perspective on brain energy metabolism and functional imaging. *Neuron* 86, 883–901, https://doi.org/10.1016/j.neuron.2015.03.035 (2015).

42. Magistretti, P. J. & Allaman, I. Lactate in the brain: from metabolic end-product to signalling molecule. *Nat Rev Neurosci* 19, 335–349, https://doi.org/10.1038/nrrn.2018.19 (2018).

43. Ferraiuolo, L. et al. Dysregulation of astrocyte-motor neuron cross-talk in mutant superoxide dismutase 1-related amyotrophic lateral sclerosis. *Brain* 134, 2627–2641, https://doi.org/10.1093/brain/awr193 (2011).

44. Cassina, P. et al. Mitochondrial dysfunction in SOD1G93A-bearing astrocytes promotes motor neuron degeneration: prevention by mitochondrial-targeted antioxidants. *J Neurosci* 28, 4115–4122, https://doi.org/10.1523/JNEUROSCIL3508-07.2008 (2008).

45. Madij Houzon, B. et al. Wildtype motorneurons, ALS-Linked SOD1 Profoundly modify astrocyte metabolism and lactate shuttling. *Glia* 65, 592–605, https://doi.org/10.1002/glia.23114 (2017).

46. Liu, L. et al. Glial lipid droplets and ROS induced by mitochondrial defects promote neurodegeneration. *Cell* 160, 177–190, https://doi.org/10.1016/j.cell.2014.12.019 (2015).

47. Liu, L., MacKenzie, K. R., Putluri, N., Maletic-Savatic, M. & Bellen, H. J. The Glia-Neuron Lactate Shuttle and Elevated ROS Promote Lipid Synthesis in Neurons and Lipid Droplet Accumulation in Glia via APOE/D. *Cell Metab.* 26, 719–737.e716, https://doi.org/10.1016/j.cmet.2017.08.024 (2017).

48. Chaves-Filho, A. B. et al. Alterations in lipid metabolism of spinal cord linked to amyotrophic lateral sclerosis. *Sci Rep* 9, 11642, https://doi.org/10.1038/s41598-019-48059-7 (2019).

49. Kis, V., Barti, B., Lippai, M. & Sass, M. Specialized Cortex Glial Cells Accumulate Lipid Droplets in Drosophila melanogaster. *PLoS One* 10, e0131250, https://doi.org/10.1371/journal.pone.0131250 (2015).

50. Henne, W. M., Reese, M. L. & Goodman, J. M. The assembly of lipid droplets and their roles in challenged cells. *EMBO J* 37, https://doi.org/10.15222/embj.201889947 (2018).

51. Thiam, A. R., Farese, R. V. & Walther, T. C. The biophysics and cell biology of lipid droplets. *Cell Metab.* 28, 1628–1633 (2019).

52. Bi, F. et al. Reactive astrocytes secrete Lcn2 to promote neuron death. *J Neurosci* 37, 693–708, https://doi.org/10.1523/JNEUROSCI.1763-16.2017 (2017).

53. Greenberg, S. A., Watts, G. D., Kimonis, V. E., Amato, A. A. & Pinkus, J. L. Nuclear localization of valosin-containing protein in normal muscle and muscle affected by inclusion-body myositis. *J Neurochem.* 126, 577–587, https://doi.org/10.1111/jn.13994 (2013).

54. Laureys, G. et al. Ultrastructural features of aberrant glial cells isolated from the spinal cord of paralytic rats expressing the amyotrophic lateral sclerosis-linked SOD1G93A mutation. *Cell Tissue Res.* 370, 391–401, https://doi.org/10.1007/s00441-017-2681-1 (2017).

55. Jimenez-Rian, M. et al. Ultrastructural features of aberrant glial cells isolated from the spinal cord of paralytic rats expressing the amyotrophic lateral sclerosis-linked SOD1G93A mutation. *Cell Tissue Res.* 370, 391–401, https://doi.org/10.1007/s00441-017-2681-1 (2017).

56. Liddelow, S. A. & Barres, B. A. Reactive Astrocytes: Production, Function, and Therapeutic Potential. *Immunity* 46, 957–967, https://doi.org/10.1016/j.immuni.2017.06.006 (2017).

57. Bozza, P. T. & Viola, J. P. Lipid droplets in inflammation and cancer. *Prostaglandins Leukot. Essent. Fatty Acids* 82, 243–250, https://doi.org/10.1016/j.pla.2010.02.005 (2010).

58. Laureys, G. et al. Astrocytic beta(2)-adrenergic receptors: from physiology to pathology. *Prog Neurobiol* 91, 189–199, https://doi.org/10.1016/j.pneurobiol.2010.01.011 (2010).

59. De Keyser, J., Zeinstra, E. & Wilczak, N. Astrocytic beta2-adrenergic receptors and multiple sclerosis. *Neurobiol. Dis.* 15, 331–339, https://doi.org/10.1016/j.nbd.2005.10.012 (2004).

60. Kawamata, H. et al. Abnormal intracellular calcium signaling and SNARE-dependent exocytosis contributes to SOD1G93A astrocyte-mediated toxicity in amyotrophic lateral sclerosis. *J Neurosci* 34, 2331–2348, https://doi.org/10.1523/JNEUROSCI.2689-13.2014 (2014).
77. Pellerin, L. & Magistretti, P. J. Glutamate uptake into astrocytes stimulates aerobic glycolysis: a mechanism coupling neuronal activity to glucose utilization. *Proc Natl Acad Sci USA* **91**, 10625–10629, https://doi.org/10.1073/pnas.91.22.10625 (1994).
78. Lee, Y. et al. Oligodendroglia metabolically support axons and contribute to neurodegeneration. *Nature* **487**, 443–448, https://doi.org/10.1038/nature11314 (2012).
79. Schwartz, J. & Wilson, D. Preparation and characterization of type I astrocytes cultured from adult rat cortex, cerebellum, and striatum. *Glia* **5**, 73–80 (1992).
80. Vardjan, N. et al. Adrenergic activation attenuates astrocyte swelling induced by hypotonicity and neurotrauma. *Glia* **64**, 1034–1049, https://doi.org/10.1002/glia.22981 (2016).
81. Kreft, M., Milisav, I., Potokar, M. & Zorec, R. Automated high throughput colocalization analysis of multichannel confocal images. *Comput Methods Programs Biomed* **74**, 63–67 (2004).
82. Prebil, M., Vardjan, N., Jensen, J., Zorec, R. & Kreft, M. Dynamic monitoring of cytosolic glucose in single astrocytes. *Glia* **59**, 903–913, https://doi.org/10.1002/glia.21161 (2011).
83. Vardjan, N. et al. Enhancement of Astroglial Aerobic Glycolysis by Extracellular Lactate-Mediated Increase in cAMP. *Front Mol Neurosci* **11**, 148, https://doi.org/10.3389/fnmol.2018.00148 (2018).

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**Author contributions**

JV performed experiments, analysed data, prepared figures and wrote the manuscript, AH performed experiments, analysed data, prepared figures and wrote the manuscript, TS performed experiments and analysed data, SPM constructed the pTagRFP::TDP-43wt and pTagRFP::TDP-43208–414 plasmids, RZ and BR conceived and directed the study, NV conceived and directed the study, analysed data, prepared figures, wrote the manuscript. All authors read and contributed to the completion of the draft manuscript.

**Competing interests**

The authors declare no competing interests.

**Additional information**

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