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Gp130-Dependent Astrocytic Survival Is Critical for the Control of Autoimmune Central Nervous System Inflammation

Fahad Haroon,* Katrin Drögemüller,* Ulrike Händel,* Anna Brunn,† Dirk Reinhold,‡ Gopala Nishanth,* Werner Mueller,§ Christian Trautwein,¶ Matthias Ernst,‖ Martina Deckert,† and Dirk Schlueter*†

Astrocytes are activated in experimental autoimmune encephalomyelitis (EAE) and have been suggested to either aggravate or ameliorate EAE. However, the mechanisms leading to an adverse or protective effect of astrocytes on the course of EAE are incompletely understood. To gain insight into the astrocyte-specific function of gp130 in EAE, we immunized mice lacking cell surface expression of gp130, the signal-transducing receptor for cytokines of the IL-6 family, with myelin oligodendrocyte glycoprotein35–55 peptide. These glial fibrillary acid protein (GFAP)-Cre gp130fl/fl mice developed clinically a significantly more severe EAE than control mice and succumbed to chronic EAE. Loss of astrocytic gp130 expression resulted in apoptosis of astrocytes in inflammatory lesions of GFAP-Cre gp130fl/fl mice, whereas gp130fl/fl control mice developed astrogliosis. Astrocyte loss of GFAP-Cre gp130fl/fl mice was paralleled by significantly larger areas of demyelination and significantly increased numbers of CD4 T cells in the CNS. Additionally, loss of astrocytes in GFAP-Cre gp130fl/fl mice resulted in a reduction of CNS regulatory Foxp3+ CD4 T cells and an increase of IL-17α, IFN-γ, and TNF-producing CD4 as well as IFN-γ and TNF-producing CD8 T cells, illustrating that astrocytes regulate the phenotypic composition of T cells. An analysis of mice deficient in either astrocytic gp130–Src homology region 2 domain-containing phosphatase 2/Ras/mitogen-activated protein kinase or gp130–signal transducer and activator of transcription 1 (STAT1) signaling revealed that prevention of astrocyte apoptosis, reduction of proinflammatory cytokines and chemokines as well as increased demyelination (2, 3). This astrocyte-specific NF-κB activation is critically regulated by IL-17–mediated activation of Akt1; in the absence of astrocytes Akt1 signaling, mice are largely protected from EAE and CD4 T cell infiltration to the spinal cord (4, 5). At later stages of EAE, reduced uptake of toxic molecules, inhibition of remyelination by scar formation, and blocking of axonal regeneration may contribute to disease progression (6, 7, reviewed in Ref. 8). However, astrocytes can also confer protection against EAE by reducing leukocyte infiltration into the CNS, induction of T cell apoptosis, production of immunosuppressive cytokines including IL-27, induction of regulatory T cells, inhibition of autoreactive T cell activation as well as enhancing myelin repair, and neuroprotection (8–14). These complex and in part opposing effects of astrocytes on EAE indicate that astrocyte function may be influenced by various factors, including the time point of disease, the local inflammatory milieu, regional differences of astrocyte function, or even astrocyte subtypes (reviewed in Refs. 8, 14).

The gp130 receptor is an essentially ubiquitous signal transducer for members of the IL-6 cytokine family, which includes IL-6, IL-11, IL-27, leukemia inhibitory factor (LIF), oncostatin M (OSM), ciliary neurotrophic factor (CNTF), B cell-stimulating factor (BSF)1, and cardiotrophin (CT)-1 (15). Gp130-deficient mice die perinatally and suffer from a more severe phenotype than mice deficient for individual gp130 ligands (for review, see 15). This
also explains why the function of gp130 is still unknown in cerebrovascular autoimmune disorders, whereas the function of gp130 ligands and coreceptors has been partially characterized. In EAE, IL-27Ra, which forms a signaling complex in combination with gp130, plays a crucially protective role by inhibiting immunopathology mediated by IL-17-producing CD4 T cells (16). In contrast, mice lacking IL-6 developed impaired autoimmune T cell responses after immunization with MOG Ag, resulting in an increased resistance to EAE (17). Further studies with CNTF–/– and LIF–/– mice have shown that gp130-dependent signal transduction is important for limiting EAE by enhancing oligodendrocyte survival (18, 19). Collectively, these data indirectly indicate a regulatory role for gp130 in autoimmune CNS disorders, but it is unknown whether responsiveness of astrocytes to gp130-stimulating cytokines impacts on the disease.

Stimulation of gp130 results in the phosphorylation of a single membrane-proximal Y residue in gp130 (Y757 in mouse gp130), which induces the recruitment of the SH2 domain-containing cytoplasmic protein tyrosine phosphatase Src homology region 2 domain-containing phosphatase 2 (SHP2), its subsequent tyrosine phosphorylation, and activation of the Ras-ERK1/2 MAPK cascade (20). In contrast, binding of STAT1 and STAT3 proteins to the membrane-distal phosphotyrosine residues within gp130 (20) results in their tyrosine phosphorylation, homo- and/or heterodimerization, nuclear translocation, and transcriptional activation of target genes. Importantly, the gp130-dependent Ras and STAT1/3 pathways negatively control each other (21). To analyze the specific function of these two signaling pathways, mice lacking either gp130-STAT or gp130-Ras signaling have been generated (21, 22).

To characterize the in vivo function of astrocytes in autoimmune CNS disorders, we induced EAE in mice that lack gp130–, gp130-STAT1/3–, gp130-Ras–, or gp130-STAT or gp130-Ras–dependent signaling specifically in astrocytes. These experiments revealed the following: 1) astrocytic gp130 expression was crucial for survival of astrocytes and development of astroglisis in EAE; 2) astrocyte loss exacerbated EAE characterized by significantly larger areas of demyelination and proinflammatory T cell response; and 3) the astrocytic gp130-SHP2/Ras/ERK pathway protected astrocytes from apoptosis and ameliorated EAE.

Materials and Methods

**Mice**

C57BL/6 human glial fibrillary acid protein (GFAP)-Cre transgenic mice (23) were bred with C57BL/6 gp130fl/fl (24) mice to generate GFAP-Cre−/− gp130fl/fl mice. To obtain Synapsin I-Cre knock-in mice, C57BL/6 Syn-Cre mice (23) were bred with C57BL/6 gp130fl/fl (24) mice to generate GFAP-Cre+/- gp130fl/fl mice. To obtain Synapsin I-Cre gp130fl/fl, gp130-SHP2/Ras/ERK, and gp130-STAT1/3– mice, GFAP-Cre+/- gp130fl/fl mice were bred with Synapsin-Cre+/- mice. An ABC protocol, as described (27).

**Induction and clinical evaluation of EAE**

MOG35–55 (MEVGWYRSPFSRVHLYRNGK) was purchased from JPT (Berlin, Germany). EAE was induced in 8– to 12-wk-old mice by s.c. immunization with 200 μg MOG35–55 in CFA (Sigma-Aldrich, Taufkirchen, Germany) containing 800 μg killed Mycobacterium tuberculosis (Sigma-Aldrich). In addition, 200 ng pertussis tox (Sigma-Aldrich), dissolved in 200 μl PBS, was injected i.p. at the day of immunization and again 2 d thereafter. In indicated experiments, mice were immunized for a second time with 200 μg MOG35–55–peptide in CFA (Sigma-Aldrich) containing 800 μg killed M. tuberculosis (Sigma-Aldrich) 7 d after primary immunization. Mice were monitored daily for clinical signs of EAE and graded on a scale of increasing severity from 0 to 5, according to a previously published grading scale (26) and detailed in Supplemental Table 1. Daily clinical scores were calculated as the average of all individual disease scores within each group.

**Histology**

For immunohistochemistry on frozen sections, mice were perfused intracardially with 0.9% NaCl in methoxyflurane anesthesia. Brains were shock frozen, and immunohistochemistry for CD45, CD25, and CD8 was performed, as described before (27). For histology on paraffin sections, anesthetized mice were perfused with 4% paraformaldehyde in PBS; brains and spinal cords were processed and stained with hemalum and eosin, cresyl violet, luxol fast blue, and periodic acid Schiff stain, and also used for immunohistochemical demonstration of GFAP, neurofilament, Mac3, and CD3, CD3 (Serotec, Düsseldorf, Germany), S100 protein (DakoCytomation, Hamburg, Germany), and GFAP were demonstrated in an ABC protocol, as described (27).

**Stereology**

To quantify numbers of astrocytes and areas of demyelination in the spinal cord, stereology was applied using a computerized stereology system (Cast Software, Olymups, Germany). Serial cross sections (4 μm) of the entire spinal cord, that is, cervical, thoracic, and lumbar level, were cut. Every third section was either stained with rat anti-mouse GFAP, slightly counterstained with hemalum, or stained with luxol fast blue and cresyl violet, respectively. The volume of the entire spinal cord and the volume of the white matter, respectively, were determined according to Cavalieri’s method (28) by estimating the area of every third section with the computerized system and multiplication with the distance to the next cross section evaluated, that is, 12 μm. Nuclei of GFAP-labeled astrocytes were counted. To avoid repetitive counting of astrocytes in adjacent cross sections, every fourth section was evaluated. Numbers of astrocytes/mm³ were compared between the experimental groups. To compare areas of demyelination, the area of gray matter plus demyelinated white matter was related to the total area of the respective cross section.

**Isolation of cerebral leukocytes and flow cytometry**

Leukocytes were isolated from brain and spinal cord and stained for CD4⁺ T cells, CD8⁺ T cells, and CD45⁺ inflammatory leukocytes, as described before (29). For intracerebral cytokine staining, isolated leukocytes were incubated with 50 ng/ml IFN-γ, 500 ng/ml IL-27, and iNOS, 10 μg/ml GolgiPlug (1 μl/ml) containing brefeldin A in MEM-α at 37˚C for 4 h. Thereafter, cells were stained with CD4-FITC and CD8-allophycocyanin; fixed and permeabilized with Cytofix/Cytoperm (BD Biosciences, Heidelberg, Germany); and stained with rat anti-mouse IL-17–PE, TNF-PE, or IFN-γ–PE (BD Biosciences). Controls included staining with isotype-matched control Abs. For the detection of regulatory and activated CD4 T cells, isolated leukocytes were incubated with CD25-PE and CD4-allophycocyanin, followed by a Foxp3-PE staining kit, as recommended by the manufacturer (NatuTec/eBiosciences, Frankfurt, Germany). Apoptotic and dead CD4 T cells were detected by staining with annexin V, 7-aminoactinomycin D (7-AAD), and CD4-allophycocyanin; fixed and permeabilized with Cytofix/Cytoperm (BD Biosciences, Heidelberg, Germany); and stained with rat anti-mouse IL-17–PE, TNF-PE, or IFN-γ–PE (BD Biosciences). Controls included staining with isotype-matched control Abs. Flow cytometry was performed on a FACSscan (BD Biosciences), and the data were analyzed with WinMDI or CellQuest software.

**Quantitative RT-PCR**

For RT-PCR, mRNA was isolated from the spinal cord of nonimmunized and MOG35–55-immunized mice (RNeasy kit; Qiagen). mRNA was transcribed into cDNA by use of a SuperScript reverse-transcriptase kit with oligo(dT) primers (Invitrogen). Quantitative PCR for the gp130 ligands IL-6, LIF, CNTF, OSM, CT-1, BSF3, IL-11, and IL-27 was performed with cDNA derived from C57BL/6 WT mice. The ratio between the respective cytokine and hypoxanthine phosphoribosyltransferase (HPRT) was calculated per mouse, and data are presented as the increase over nonimmunized mice. Quantitative RT-PCR for IL-17, IFN-γ, IL-23, inducible NO synthase (iNOS), TNF, TGF-β2, IL-27, and HPRT was performed with cDNA from GFAP-Cre+/- gp130fl/fl, gp130-STAT1/3– mice with the GeneAmp 5700 sequence detection system (Applied Biosystems, Foster City, CA). Quantitation was performed with the sequence detector software SDS 2.1 (Applied Biosystems), according to the ΔΔ cycle threshold method (30) with HPRT as housekeeping gene. Data are expressed as increase of mRNA expression in...
immunized mice over nonimmunized controls of the respective mouse strain. All primers and probes were obtained from Applied Biosystems.

**Statistics**

Demyelinated areas and astrocyte numbers were evaluated on serial 4-μm cross sections of the spinal cord, which were either stained with luxol fast blue and cresyl violet or anti-GFAP and hemalum, respectively. Every third section was evaluated. For statistical evaluation of the number of GFAP+ astrocytes on GFAP-immunostained sections, at least 50 high power fields (final original magnification ×400), randomly selected from all areas of various regions of the spinal cord, were analyzed per section in three animals per group. Differences were analyzed with the nonparametric Mann-Whitney rank sum test. To test for statistical differences in the survival rate, clinical scores, and cell numbers, the two-tailed Student t test was used. The p values <0.05 were accepted as significant. All experiments were performed at least twice.

**Results**

**Upregulation of gp130 ligands in EAE**

Because the gp130 receptor is essential for signal transduction of molecules of the IL-6 cytokine family, we analyzed whether expression of single or multiple members of this family is regulated in the spinal cord of mice suffering from EAE. At 14 d post-immunization (p.i.), expression of IL-6, LIF, OSM, and IL-27 was markedly upregulated, whereas expression of CNTF; CT-1, BSF3, and IL-11 was unaltered (Fig. 1). At this stage of EAE, mice had a mean clinical score of 2.2, and up to 25 d p.i. clinical scores declined to 0.9. In parallel to regressing disease activity, mRNA levels of IL-6, LIF, OSM, and IL-27 declined, although levels of LIF and OSM were still increased as compared with nonimmunized mice (Fig. 1).

**Aggravated EAE of GFAP-Cre gp130<sup>fl/fl</sup>**

To study the functional role of astrocytic gp130 expression, we used GFAP-Cre gp130<sup>fl/wt</sup> mice, which lack gp130 cell surface expression on astrocytes (31). We have previously shown that in this mutant macroscopically and histopathologically brain architecture is normal, including a regular number and morphology of GFAP<sup>+</sup> astrocytes (31).

Clinically, GFAP-Cre gp130<sup>fl/wt</sup> mice developed a significantly more severe EAE as compared with gp130<sup>fl/wt</sup> control mice upon immunization with MOG<sub>35-55</sub> (Fig. 2A; for definition of clinical score, see Supplemental Table 1). In addition, GFAP-Cre gp130<sup>fl/fl</sup> mice did not recover from disease and 50–84% died of EAE. In contrast, only 10–15% of controls died of EAE.

To analyze whether differences in clinical disease activity between the two groups were influenced by the strength of immunization, mice were immunized for a second time with MOG<sub>35-55</sub> peptide 7 d after primary immunization. Double immunization resulted in a higher maximal clinical score without subsequent decline in gp130<sup>fl/wt</sup> mice as compared with single-immunized mice (Fig. 2B). In GFAP-Cre gp130<sup>fl/wt</sup> mice, double immunization induced a very rapid progression of clinical symptoms, and peak scores developed within 5 d after disease onset without regression thereafter (Fig. 2B). Because single immunization was sufficient to induce maximal disease scores in GFAP-Cre gp130<sup>fl/wt</sup> mice, we used the single-immunization protocol in further experiments.

To exclude that a genotoxic effect of Cre causes the more severe disease of GFAP-Cre gp130<sup>fl/wt</sup> mice, we induced EAE in normal WT (gp130<sup>wt/wt</sup>) and GFAP-Cre gp130<sup>wt/wt</sup> mice. As illustrated in Supplemental Fig. 1, the clinical course of EAE was identical in both strains of mice, excluding a genotoxic effect of GFAP-Cre in our experiments.

Because GFAP-Cre–driven deletion of gp130 also results in lack of gp130 expression in ~10% of neurons (31), we also established mice with neuron-specific, Synapsin I-Cre–mediated deletion of gp130 (Supplemental Fig. 2A–C). It has been shown before that Synapsin I-Cre efficiently deletes genes in the vast majority of neurons in all regions of the CNS, including the spinal cord (25). Importantly, Synapsin I-Cre gp130<sup>fl/wt</sup> mice showed the same course of EAE as gp130<sup>fl/wt</sup> mice (Supplemental Fig. 2D), demonstrating that the absence of gp130 on astrocytes, but not on neurons, is responsible for aggravation of EAE in GFAP-Cre gp130<sup>fl/fl</sup> mice.

**Astrocyte loss in GFAP-Cre gp130<sup>fl/fl</sup> mice with EAE**

To study the impact of astrocyte-specific gp130 expression on EAE challenge, a detailed stereological analysis was performed. Numbers of astrocytes in the spinal cord of GFAP-Cre gp130<sup>fl/fl</sup> mice were significantly increased in GFAP-Cre gp130<sup>fl/fl</sup> mice as compared with gp130<sup>fl/fl</sup> mice (*p < 0.05, **p < 0.01). Data from one of three (A) and one of two (B) independent experiments are shown.

**FIGURE 1.** Upregulation of IL-6 family cytokine mRNA in EAE. mRNA transcription of IL-6 family cytokine members in the spinal cord was evaluated by quantitative RT-PCR in nonimmunized and MOG<sub>35-55</sub>–immunized C57BL/6 mice at 14 and 25 d p.i. Data are expressed as increase of the respective cytokine mRNA of immunized over nonimmunized mice normalized to HPRT expression. Three mice per group were analyzed. Data represent the mean ± SEM. Data from one of two independent experiments are shown.

**FIGURE 2.** Increased clinical EAE severity in GFAP-Cre gp130<sup>fl/fl</sup> mice. A and B. The clinical scores of GFAP-Cre gp130<sup>fl/wt</sup> and gp130<sup>fl/fl</sup> mice were monitored daily up to 60 d after single (A) or double (B) immunization with MOG<sub>35-55</sub> peptide. Data show the mean ± SEM. Eight to 10 (A) and six (B), respectively, mice per experimental group were analyzed. At 20 and 60 d p.i., clinical score and disease incidence were significantly increased in GFAP-Cre gp130<sup>fl/fl</sup> mice as compared with gp130<sup>fl/wt</sup> mice (*p < 0.05, **p < 0.01). Data from one of three (A) and one of two (B) independent experiments are shown.
mice were significantly reduced as compared with gp130fl/fl control animals (Fig. 3A). In GFAP-Cre gp130fl/fl mice, astrocyte loss was observed at all levels of the spinal cord, that is, the cervical, thoracic, and lumbar segment. In addition to this three-dimensional analysis of astrocyte numbers, standard immunohistochemistry showed a gradual loss of astrocytes within inflammatory and demyelinated lesions over time in GFAP-Cre gp130fl/fl mice (Fig. 3B). In contrast, the number of activated astrocytes increased in inflammatory lesions of control mice and was significantly increased in comparison with GFAP-Cre gp130fl/fl mice at all time points after MOG35–55 immunization (Fig. 3B). Interestingly, astrocyte numbers of gp130fl/fl mice also increased in noninflamed regions of the spinal cord and were significantly higher as compared with GFAP-Cre gp130fl/fl mice at 42 d.p.i. (Fig. 3B).

As early as 14 d.p.i., the decline in astrocyte numbers in inflammatory lesions of GFAP-Cre gp130fl/fl mice was paralleled by the frequent appearance of astrocytes with crinkled processes and a condensed nucleus, indicating their apoptosis (Fig. 3C). Activated, hypertrophic GFAP+ astrocytes were only rarely observed in the lesions of GFAP-Cre gp130fl/fl mice (Fig. 3D). These findings became more prominent with disease progression, and the inflammatory lesions of GFAP-Cre gp130fl/fl mice were nearly completely devoid of astrocytes at 42 d.p.i. (data not shown). In contrast, activated astrocytes in inflammatory lesions of control
mice upregulated GFAP and were hypertrophic with long and extended cellular processes resulting in astrogliosis (Fig. 3D, 3F). Combined TUNEL and GFAP staining revealed that at all time points of EAE, astrocytes of GFAP-Cre gp130<sup>fl/fl</sup> mice underwent apoptosis. Most of the TUNEL<sup>+</sup> cells still exhibited a faint GFAP staining, which is compatible with a rapid degradation of this cytoskeletal protein (Fig. 3E). In contrast, only a few GFAP<sup>+</sup> astrocytes were TUNEL<sup>+</sup> in gp130<sup>fl/fl</sup> mice (Fig. 3F). These findings indicate that gp130 expression of astrocytes is important for the protection of astrocytes against apoptosis and results in the development of astrogliosis in EAE.

**Increased pathology and persistence of inflammatory infiltrates in EAE of GFAP-Cre gp130<sup>fl/fl</sup> mice**

A histopathological analysis of the impact of astrocytic loss on demyelination and the inflammatory response in EAE revealed that GFAP-Cre gp130<sup>fl/fl</sup> mice exhibited a remarkably more pronounced demyelination in the caudal brain stem and the spinal cord than control mice (Fig. 4A, 4C). The demyelinated area was significantly enlarged in GFAP-Cre gp130<sup>fl/fl</sup> mice as compared with control animals (Fig. 4E). Whereas inflammation and demyelination were largely confined to the dorsal columns of the spinal cord in gp130<sup>fl/fl</sup> mice, inflammatory demyelination also affected the lateral and anterior areas of the spinal cord and also extended into the gray matter of the spinal cord of GFAP-Cre gp130<sup>fl/fl</sup> mice (Fig. 4A). The more widespread inflammation and demyelination persisted in chronic EAE of GFAP-Cre gp130<sup>fl/fl</sup> mice, when gp130<sup>fl/fl</sup> mice had already clinically recovered (Fig. 4B, 4D). Flow cytometric quantification of inflammatory leukocytes confirmed that numbers of leukocytes were significantly increased in the CNS of GFAP-Cre gp130<sup>fl/fl</sup> as compared with gp130<sup>fl/fl</sup> mice (Fig. 4F).

**Increased numbers of CD4 T cells were paralleled by a reduction of regulatory CD4 T cells and an increase of proinflammatory cytokine-producing T cells in GFAP-Cre gp130<sup>fl/fl</sup> mice**

Because autoimmune T cells are crucial for EAE development, we studied the distribution of T cells at an early (14 d p.i.) and late stage (42 d p.i.) of EAE. CD3<sup>+</sup> T cell infiltrates were present in both GFAP-Cre gp130<sup>fl/fl</sup> and control mice at 14 d p.i. Up to 42 d p.i., however, they had persisted only in GFAP-Cre gp130<sup>fl/fl</sup> mice, whereas they had largely been resolved in gp130<sup>fl/fl</sup> mice (Fig. 5A–D).

At 17 d p.i., a flow cytometric analysis of T cells revealed that GFAP-Cre gp130<sup>fl/fl</sup> mice harbored 2-fold more CD4 T cells in the CNS than gp130<sup>fl/fl</sup> control animals (Fig. 5E), which already started to recover from an EAE. In contrast, numbers of CD8 T cells did not differ significantly between the two genotypes (Fig. 5E).

It has been suggested that astrocytes induce apoptosis of autoimmune CD4 T cells (32), which may explain the increased numbers of CD4 T cells in GFAP-Cre gp130<sup>fl/fl</sup> mice. However, only in two of four experiments was a reduced percentage of 7-AAD<sup>−</sup> CD4 T cells obvious in GFAP-Cre gp130<sup>fl/fl</sup> mice. In addition, the percentage of active caspase-3<sup>+</sup> CD4 T cells was not reduced in GFAP-Cre gp130<sup>fl/fl</sup> mice (3.3 versus 5.9% in gp130<sup>fl/fl</sup> and GFAP-Cre gp130<sup>fl/fl</sup> mice, respectively), as revealed by flow cytometry.

In addition, astrocyte apoptosis influenced the activation and the phenotypic composition of CD4 T cells in EAE. The percentage of both Foxp3<sup>+</sup> CD25<sup>+</sup> and Foxp3<sup>+</sup> CD25<sup>+</sup> regulatory CD4 T cells was reduced in GFAP-Cre gp130<sup>fl/fl</sup> mice, whereas the number of activated Foxp3<sup>−</sup> CD25<sup>+</sup> effector CD4 T cells was increased as compared with control mice (Fig. 5F).

These differences in the number of regulatory and activated CD4 T cells were paralleled by an increase of IL-17<sup>+</sup>, TNF<sup>−</sup>, and IFN-γ–producing CD4 as well as TNF<sup>−</sup>- and IFN-γ–producing CD8 T cells in the CNS of GFAP-Cre gp130<sup>fl/fl</sup> mice as compared with control animals (Fig. 5G, 5H). The increase of CD4 T cells was 4-fold for IL-17 and 3-fold for both TNF and IFN-γ, respectively. Thus, the increase in the number of cytokine-producing CD4 T cells exceeded the 2-fold difference in the absolute number of CD4 T cells in the CNS of GFAP-Cre gp130<sup>fl/fl</sup> mice (Fig. 5E). Similar observations were obtained for CD8 T cells, as follows: there was a 2-fold increase for TNF<sup>−</sup> and a 4-fold increase in IFN-γ–producing CD8 T cells in GFAP-Cre gp130<sup>fl/fl</sup> mice, respectively, despite a lack of difference in the absolute number of CD8 T cells in both strains of mice (Fig. 5E). Thus, astrocyte loss was associated with an increase of disease-promoting T cells, whereas protective T cell populations declined.
Increased IL-17, IFN-γ, IL-23, and iNOS mRNA production of GFAP-Cre gp130^{fl/fl} mice

To gain further insight into the impact of astrocytes on cytokine production in EAE, cytokine mRNA transcription in the spinal cord was analyzed at an early (14 d p.i.) and a late time point (21 d p.i.) of EAE. At 14 d p.i., IL-17 mRNA was strongly upregulated in GFAP-Cre gp130^{fl/fl} mice as compared with control animals (Fig. 6A). In contrast, IFN-γ, IL-23, TNF, iNOS, TGF-β2, and IL-27 mRNA did not differ between the two mouse strains at this time point (Fig. 6B–G). In addition to IL-17 mRNA, IFN-γ, IL-23, and iNOS mRNA were also strongly upregulated in GFAP-Cre gp130^{fl/fl} mice at 21 d p.i. In contrast, TGF-β2 mRNA was increased in gp130^{fl/fl} mice at this stage of EAE. No differences were observed for TNF and IL-27.

The gp130-SHP2/Ras/ERK, but not the gp130-STAT pathway ameliorates EAE, protects astrocytes from apoptosis, and reduces inflammatory infiltrates as well as demyelination

Ligand engagement of the gp130 receptor results in activation of the STAT1/3 and Ras/ERK pathway via specific tyrosine residues within the cytosolic portion of gp130. To evaluate the contribution
of the two pathways to ameliorate EAE, we used a breeding strategy to generate pseudo-tissue–specific mutant mice that harbored either one gp130ΔSTAT allele (resulting in the lack of STAT1/3 and excessive SHP2/Ras/ERK activation) or one gp130757F allele (resulting in the lack of SHP2/Ras/ERK and excessive STAT1/3 activation) (33). Accordingly, these mutant alleles become functionally dominant in astrocytes following inbreeding with GFAP-Cre gp130Δfl mice and upon stimulation with IL-6 family ligands, in the resulting compound GFAP-Cre gp130ΔΔSTAT and GFAP-Cre gp130757F mice.

Upon immunization with MOG35–55 peptide, GFAP-Cre gp130ΔΔSTAT mice developed EAE clinically similar to gp130Δfl control mice. In contrast, clinically GFAP-Cre gp130757F mouse suffered from much more severe symptoms than gp130-proficient control mice. Indeed, GFAP-Cre gp130ΔY757F mice showed similar EAE scores to gp130-deficient GFAP-Cre gp130Δfl/mice (Fig. 7A). Histopathological analysis of GFAP-Cre gp130ΔY757F mice revealed a strong and widespread loss of astrocytes in the spinal cord (Fig. 7B) similar to that observed in GFAP-Cre gp130Δfl mice, whereas astrocytes of GFAP-Cre gp130ΔΔSTAT mice were activated and hypertrophic despite a less severe disease activity (Fig. 7C). Loss of astrocytes in GFAP-Cre gp130ΔY757F mice resulted in much more severe demyelination when compared with GFAP-Cre gp130ΔΔSTAT mice, which showed only mild demyelination (Fig. 7D, 7E). Consistent with the different extent of demyelination, inflammatory infiltrates were much more prominent and widespread in GFAP-Cre gp130ΔY757F mice than in GFAP-Cre gp130ΔΔSTAT mice (Fig. 7F, 7G). Collectively, these observations suggest that the extent of gp130-mediated STAT activation in astrocytes, which occurs excessively in GFAP-Cre gp130ΔY757F mice and is absent from GFAP-Cre gp130Δfl mice, is not related to development of EAE. In contrast, the extent of EAE inversely correlates with the extent of gp130-mediated SHP2/Ras/ERK activation, which is absent in the highly disease-sensitive GFAP-Cre gp130ΔΔSTAT and GFAP-Cre gp130Δfl strains, but present in gp130Δfl controls and GFAP-Cre gp130ΔΔ STAT mice. Therefore, we conclude that development of a protective astrogliosis is independent of gp130-mediated STAT signaling, but requires gp130-dependent SHP2/Ras/ERK signaling.

**Discussion**

The present in vivo experiments revealed that astrocyte-specific gp130 signaling is important to protect mice from EAE, because both single and double MOG35–55-immunized mice lacking astrocyte-specific gp130 signaling developed a clinically significantly more severe EAE than control mice. The major protective function of astrocytic gp130 was to ensure astrocyte survival and to enable development of astrogliosis as important factors limiting autoimmune T cell reactions and demyelination in EAE. Such an important function of gp130 expression on astrocytes in EAE has not been observed in mice lacking individual gp130 ligands, including IL-6, LIF, and IL-27, respectively (16, 17, 34). However, all of these gp130 ligands were upregulated in EAE and, therefore, may compensate for each other in rescuing astrocytes from apoptosis under inflammatory conditions. This is in contrast to oligodendrocytes, which requireCNTF and LIF to prevent their apoptosis in EAE (18, 19). The cell-type–specific importance of astrocytic gp130 is further stressed by the observation that mice lacking gp130 expression selectively in neurons developed the same course of EAE as gp130Δfl control mice.

Gp130 expression of astrocytes was required to prevent apoptosis of astrocytes. In good agreement with an antiapoptotic function of gp130 (35), survival of astrocytes upon in vitro stimulation with TNF is gp130 dependent (31). Because in EAE a variety of cytokines including TNF is produced (36) (Figs. 5, 6), these molecules may also contribute to loss of GFAP-Cre gp130Δfl astrocytes in vivo.

Astrocyte apoptosis rendered GFAP-Cre gp130Δfl mouse unable to mount astrogliosis in EAE. Recent studies in EAE using inducible astrocyte-deficient mice demonstrated that deletion of astrocytes in EAE prevents the development of astrogliosis, resulting in a more widespread inflammation and demyelination (10). Interestingly, we demonstrated previously that in Toxoplasma encephalitis gp130-dependent astrocyte survival and astrogliosis are important to restrict and contain inflammatory lesions (31). The concept of gp130-dependent astrogliosis as a CNS intrinsic and specific mechanism to restrict inflammatory...
lesions is supported by the more widespread inflammation and demyelination in EAE of GFAP-Cre gp130fl/Y757F mice. Interestingly, patients suffering from acute multiple sclerosis are also characterized by astrocyte loss in the center of the demyelinated lesions and an astrogliosis surrounding these lesions (37).

Abrogation of gp130 signaling in astrocytes had a strong impact on the immune response in the CNS. The most striking observation was that loss of astrocytes in inflammatory lesions resulted in increased numbers of CD4 T cells in the CNS. Initially, GFAP-Cre gp130fl/fl mice recruited CD3 T cells to the CNS similar to control mice. This observation indicates that the early recruitment of T cells to the CNS was unimpaired in GFAP-Cre gp130fl/fl mice and that astrocytes were still able to contribute to T cell recruitment by their production of chemokines (38). However, once autoimmune inflammation was fully established, defective astrocytic gp130 signaling and rapid astrocyte apoptosis contributed to a failure to efficiently reduce CD4 T cell numbers in the CNS.

Previous experiments have demonstrated that the elimination of autoimmune T cells by apoptosis is important for EAE resolution (39, 40). Although it is at present unclear which cell types induce CD4 T cell apoptosis in EAE, astrocytes may be key inducers because of the following: 1) astrocytes are in intimate contact with apoptotic T cells and express Fas ligand (9); 2) autoreactive CD4 T cells are Fas+ (41); and 3) Fas ligand+ astrocytes induce apoptosis of MOG-specific T cells in vitro (42). However, flow cytometry showed only reduced numbers of 7-AAD+, that is, late apoptotic or dead, CD4 T cells and failed to detect reduced active...
caspase-3 expression in CNS CD4 T cells of GFAP-Cre gp130fl/fl mice in two of four experiments. These data indicate that gp130 expression of astrocytes is not crucial for the induction of CD4 T cell apoptosis, although they do not principally rule out the possibility that astrocytes may induce apoptosis of autoimmune CD4 T cells.

The increased number of CD4 T cells in the CNS might also be caused by an increased homing of these cells to the spinal cord of GFAP-Cre gp130fl/fl mice. Our observation of a strong reduction in the number of perivasular astrocytes in inflamed areas of the spinal cord of GFAP-Cre gp130fl/fl mice and the observation of Voskuhl et al. (10) that depletion of proliferating astrocytes in EAE results in an increased influx of inflammatory leukocytes into the spinal cord indicate that perivascular astrocytes restrict the recruitment of CD4 T cells to the CNS. Thus, both activated perivasular and parenchymal astrocytes surrounding inflammatory lesions appear to restrict homing and spread of CD4 T cells to and within the CNS. Mutually not exclusive, the elevated and sustained production of proinflammatory mediators in the spinal cord of GFAP-Cre gp130fl/fl mice (Fig. 5) may contribute to the increased recruitment of autoimmune CD4 T cells and may induce a self-amplifying loop sustaining ongoing inflammation and demyelination. Interestingly, reactive astrocytes also restrict leukocyte infiltration, demyelination, tissue destruction, and motor deficits after traumatic spinal cord injury (43), which further argues for an immunosuppressive function of astrogliosis. However, astrogliosis may not always be protective, because reactive astrocytes inhibit axonal regeneration after spinal cord injury (44) and may prevent oligodendrocyte invasion into demyelinated areas in EAE (7).

In good agreement with Trajkovic et al. (12), who showed that astrocytes can induce regulatory T cell mitigating EAE, we observed that astrocyte loss in GFAP-Cre gp130fl/fl mice did not only result in an increase of activated CD25+CD4 T cells, but also in a decrease of Foxp3+ regulatory CD4 T cells. Because regulatory CD4 T cells play an important protective role in EAE (45), their decline in GFAP-Cre gp130fl/fl mice most likely directly contributes to the more severe course of EAE. These phenotypic changes were associated with a significant increase of IL-17–, IFN-γ–, and TNF-producing CD4 T cells in GFAP-Cre gp130fl/fl mice. This increase clearly exceeded the absolute increase of CD4 T cell number in GFAP-Cre gp130fl/fl mice as compared with control animals, which indicates that gp130 signaling in astrocytes is important to shift the balance between protective and EAE-inducing CD4 T cells toward protective T cells. Interestingly, previous in vitro data also provided evidence that astrocytes induce a regulatory phenotype in autoimmunity CD4 T cells (12). In addition, CD8 T cells of GFAP-Cre gp130fl/fl mice produced more IFN-γ and TNF. Thus, although gp130-dependent astrocyte loss did not affect the absolute number of CD8 T cells, their proinflammatory cytokine production was increased.

Quantitative RT-PCR revealed that transcription of IL-17, IFN-γ, IL-23, and TNF mRNA was also increased in the CNS of GFAP-Cre gp130fl/fl mice suffering from EAE. IL-17 (46) and IL-23 (47) and TNF. Thus, although gp130-dependent astrocyte loss did not affect the absolute number of CD8 T cells, their proinflammatory cytokine production was increased.

In this study, we extended our previous genetic approach to dissect the contribution of the two major intracellular signaling cascades engaged by gp130 by creating compound mutant mice that are heterozygous for the corresponding gp130 signaling mutant alleles. These alleles become functionally dominant in astrocytes upon GFAP-Cre–mediated tissue-specific ablation of the paired, conditional gp130 WT allele. Diminished activation of the gp130-STAT2/Ras/ERK pathway in GFAP-Cre gp130fl/Y757F mice reproduced all pathological features observed in gp130 signaling-deficient GFAP-Cre gp130fl/fl mice, including astrocyte loss, lack of astrogliosis, a significantly more severe clinical course, increased T cell infiltration, and severe demyelination. Noteworthily, mice lacking gp130-STAT2/Ras/ERK signaling in all cells may develop spontaneous autoimmune arthritis due to excessive activation of the STAT1/3 pathway in nonhematopoietic cells (53). Although in our model GFAP-Cre gp130fl/Y757F mice with excessive activation of STAT in astrocytes, that is, a nonhematopoietic cell type, showed an exaggerated course of EAE and astrocyte apoptosis, the augmented autoimmune reaction was largely independent of astrocytic gp130-STAT1/3 signaling, because gp130 signaling-deficient GFAP-Cre gp130fl/fl mice reproduced all features of GFAP-Cre gp130fl/Y757F mice. In sharp contrast, GFAP-Cre gp130fl/ΔSTAT mice with intact gp130-STAT2/Ras/ERK signaling developed remarkably milder clinical symptoms as compared with GFAP-Cre gp130fl/Y757F and GFAP-Cre gp130fl/fl mice due to an astrocyte-dependent reduction of autoimmune T cells in the CNS. Noteworthily, our genetic approach in GFAP-Cre gp130fl/ΔSTAT mice is designed to leave STAT1/3 activation by gp130-independent pathways, including the epidermal growth factor and IL-10 signaling, intact. Because STAT3 can be activated by various signaling pathways (reviewed in Ref. 54), STAT3-dependent astrogliosis after spinal cord injury (55) may be caused by the cumulative defective signaling of various pathways and explains why GFAP-Cre gp130fl/ΔSTAT mice still develop astrogliosis in our model. Interestingly, apoptosis of astrocytes in EAE was suppressed by gp130-mediated activation of the SHP2/Ras/ERK pathway and not that of STAT1/3 despite the observation that excessive STAT3 activation provides an antiapoptotic signal in many other cell types (56). In contrast, both astrogliosis and LIF-mediated cardiomyocyte hypertrophy are dependent on the gp130-STAT2/Ras/ERK signaling pathway (57). Collectively, this points to cell-type– and disease-specific functions of these two signaling pathways and establishes astrocytes as an important regulator of cerebral autoimmune reactions.

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Disclosures

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