

# Interleukin-6/STAT3 Pathway Signaling Drives an Inflammatory Phenotype in Group A Ependymoma

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## Abstract

Ependymoma (EPN) in childhood is a brain tumor with substantial mortality. Inflammatory response has been identified as a molecular signature of high-risk Group A EPN. To better understand the biology of this phenotype and aid therapeutic development, transcriptomic data from Group A and B EPN patient tumor samples, and additional malignant and normal brain data, were analyzed to identify the mechanism underlying EPN Group A inflammation. Enrichment of IL6 and STAT3 pathway genes were found to distinguish Group A EPN from Group B EPN and other brain tumors, implicating an IL6 activation of STAT3 mechanism. EPN tumor cell growth was shown to be dependent on STAT3 activity, as demonstrated using shRNA knockdown and pharmacologic inhibition of STAT3 that blocked proliferation and induced apoptosis. The inflammatory factors secreted by EPN tumor cells were shown

to reprogram myeloid cells, and this paracrine effect was characterized by a significant increase in pSTAT3 and IL8 secretion. Myeloid polarization was shown to be dependent on tumor secretion of IL6, and these effects could be reversed using IL6-neutralizing antibody or IL6 receptor-targeted therapeutic antibody tocilizumab. Polarized myeloid cell production of IL8 drove unpolarized myeloid cells to upregulate CD163 and to produce a number of proinflammatory cytokines. Collectively, these findings indicate that constitutive IL6/STAT3 pathway activation is important in driving tumor growth and inflammatory cross-talk with myeloid cells within the Group A EPN microenvironment. Effective design of Group A-targeted therapy for children with EPN may require reversal of this potentially immunosuppressive and protumor pathway. *Cancer Immunol Res*; 3(10); 1165–74. ©2015 AACR.

## Introduction

Molecular subgroups of primary ependymoma (EPN) have recently been defined, including two main EPN subgroups arising in the posterior fossa, termed Groups A and B, that confer different biologic phenotypes and clinical courses (1–3). Phenotypically, Group A tumors occur in younger children and are characterized by upregulation of a variety of pathways, including angiogenesis, mesenchymal cell differentiation, cell proliferation, and inflammatory response, that are hallmarks of aggressive tumor biology.

Group A designation confers increased recurrence risk and poorer overall outcome. The difference in outcome for Group A and Group B tumors is seen at relapse where most Group B patients can be salvaged by surgery and radiation while most Group A patients will go on to subsequent relapses, which almost invariably results in death (3). Group B tumors generally occur in adolescents and young adults and overexpress genes involved in ciliogenesis, microtubule assembly, and oxidative metabolism.

A recent study by our group identified inflammatory response as the predominant ontology distinguishing Group A from Group B tumors at presentation [normalized enrichment score (NES) = 3.98; false discovery rate (FDR) q-value < 0.001; ref. 3]. Upregulation of inflammatory genes was also seen in independent Group A cohorts (1, 2). In the original study that delineated posterior fossa EPN into Groups A and B, inflammatory response genes were significantly enriched in the Heidelberg-cohort Group A tumors (NES = 1.93; FDR q = 0.016; ref. 1). A second independent study also identified inflammatory response as the second highest enriched geneset in Group A EPN (FDR q < 0.0005; ref. 2). It is widely accepted that many tumors arise from and are promoted by an inflammatory microenvironment (4, 5). This hallmark of cancer is thought to be tumorigenic in part due to suppression of host antitumor immunity. Accordingly, support for the existence of an immunosuppressive phenotype in Group A EPN was previously demonstrated by the identification of an exhausted phenotype in tumor-infiltrating T cells (3). Abrogation of

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detrimental immune phenotypes in cancer has now emerged as a novel goal for experimental therapeutic approaches (6). To identify similar clinical approaches for refractory Group A EPN, this study sought to identify the mechanism driving the inflammatory phenotype of these tumors. We show that a potential molecular mechanism underlying Group A EPN inflammatory phenotype is constitutive activation of the IL6/STAT3 pathway and cross-talk between tumor and immune cells within the tumor microenvironment (TME).

Our study is the first to identify persistent IL6/STAT3 activation as a driver of tumor growth and an associated inflammatory microenvironment in Group A EPN. Targeting the IL6/STAT3 pathway, either directly or by modifying the proinflammatory microenvironment, is a potential therapeutic approach to improve patient survival and outcomes in this deadly tumor of childhood.

## Materials and Methods

### Transcriptomic analysis

The primary EPN study cohort consisted of 21 primary Group A and 20 primary Group B posterior fossa EPN and 9 supratentorial EPN. A broader transcriptomic analyses utilized EPN samples obtained at relapse (8 Group A and 6 Group B) and other pediatric and adult brain tumors. This consisted of 17 atypical teratoid/rhabdoid tumors (AT/RT); 14 pediatric and 7 adult high-grade gliomas (HGG); 8 sonic hedgehog, 5 Group 3 and 7 Group 4 medulloblastomas (MED); and 15 pilocytic astrocytoma (PA). Normal brain samples ( $n = 13$ ) were also included in this analysis, obtained from autopsy and epilepsy surgery from both infra- and supratentorial anatomic sites. All patient samples were obtained with consent (COMIRB 95-500). Tumor samples were processed identically at our institution and analyzed using the Human Genome U133plus2 Array (Affymetrix) platform as described previously (3). Microarray. CEL datafiles were background corrected and normalized using the guanine cytosine robust multi array average (gcRMA) algorithm resulting in  $\log_2$  expression values (7). To reduce error associated with multiple testing, a filtered list was created containing the highest expressed probe across all samples for each gene that possessed multiple probe sets. This list was further filtered to remove probe sets that were expressed below a threshold level that denoted absence of expression in any sample. These microarray data have been deposited in the National Center for Biotechnology Information Gene Expression Omnibus (GEO) database (8) and are publicly accessible through GEO Series accession number GSE66354 (<http://www.ncbi.nlm.nih.gov/geo/query/acc.cgi?acc=GSE66354>). Primary EPN were assigned to consensus molecular subgroups using nonnegative matrix factorization (NMF) available through the Broad Institute Gene Pattern platform (Supplementary Fig. S1; ref. 9).

Geneset enrichment analysis (GSEA) was used to examine enrichment of genes in predefined reference sets that are based on biologic knowledge using tools available from the Broad Institute Molecular Signatures Database (MSigDB; <http://www.broadinstitute.org/gsea/msigdb>; ref. 10).

### Tumor versus myeloid cell transcriptome analysis

To determine the distribution of transcripts of interest between tumor cells and tumor-associated myeloid cells, we performed transcriptomic analysis on populations that had been isolated

from patient surgical samples by tissue disaggregation and flow cytometric sorting as described previously (3). Briefly, resected tumor was finely minced with a razor and further triturated by vigorous pipetting. A single-cell suspension was obtained by passing the sample through a 70- $\mu$ m cell strainer (Becton Dickinson) of sufficiently large pore size to permit passage of all immune and tumor cells but not clumped tumor cells. Disaggregated cells were viably frozen in standard freezing media containing 10% DMSO and stored in liquid nitrogen for subsequent analysis. Isolation of tumor and myeloid subpopulations was performed by staining disaggregated samples with anti-CD45-FITC and anti-CD11b-APC antibodies (Becton Dickinson clones 2D1 and ICRF44, respectively) followed by flow sorting using a Beckman-Coulter MoFlo XDP-100. RNA was isolated from sorted cells using a microRNeasy kit (Qiagen). Extracted RNA was amplified using the Nugen WT-Ovation One-Direct System (NuGEN Technologies) that reverse transcribes RNA to cDNA, which is amplified during SPIA amplification, a linear isothermal DNA amplification process resulting in end-products of single-strand DNA. Amplified RNA was labeled (NuGEN Encore Biotin Module) and hybridized to Affymetrix Human Genome U133plus2 chips. Microarray. CEL file data were normalized as described above.

### Cytokine release assay

Viably frozen disaggregated tumor samples were thawed and flow sorted to separate immune cells from tumor cells as previously described (3). Tumor cells were cultured in 1 mL optiMem media supplemented with 15% FBS (O15) for 96 hours on ultra-low attachment plates. Media were harvest and immediately frozen at  $-80^{\circ}\text{C}$  for later use. A high sensitivity Milliplex Map kit (Millipore) was used to measure the concentration of 13 common cytokines [GM-CSF, IFN $\gamma$ , IL1 $\beta$ , IL2, IL4, IL5, IL6, IL7, IL8, IL10, IL12 (p70), IL13, and TNF $\alpha$ ] as per the manufacturer's instructions. IL6 secretion in media from cell lines was also measured using Quantikine ELISA human IL6 (R&D Systems) according to the manufacturer's instructions.

### Western immunoblots

Primary antibodies used were pSTAT3 (Tyr-705; cat# 9145 clone D3A7), STAT3 (cat# 9139 clone 124H6), suppressor of cytokine signaling 3 (SOCS3; cat# 2923), myeloid cell leukemia sequence 1 (BCL2-related; MCL1; cat# 5453 clone D35A5; Cell Signaling Technologies). Anti- $\beta$ -actin (cat# 12262 clone 8H10D10; Cell Signaling Technologies) was used as the protein loading control. Membranes were blocked in TBS-Tween 5% milk or BSA depending on the manufacturer's recommendation. Bands were visualized with Immobilon Western Chemiluminescent HRP substrate (Millipore) on X-ray film, and densitometry measurements were performed. All experiments were performed three times, and representative blots are shown.

### Cell lines

EPN cell line 811 was established from the fourth recurrence in a patient with metastatic anaplastic EPN that exhibited a Group A phenotype. This unique cell line is positive for chromosome 1q gain (1q+) as was the tumor. 1q+ is known to be a poor risk factor for EPN. This cell line was maintained under normal culture conditions in OptiMem media supplemented with 15% FBS (O15; Invitrogen). Patient samples were obtained with consent (COMIRB#95-500). Glioblastoma (GBM) cell line U87, obtained

from ATCC, was cultured in MEM supplemented with 10% FBS, nonessential amino acids, sodium pyruvate, and sodium bicarbonate. Conditioned media (CM) from cell lines, as used for characterization of cytokine release and monocyte polarization, were obtained by harvesting media from a known number of cells after 24-hour incubation. Cell line authentication was performed using short tandem repeat profiling and comparison with known cell line DNA profiles.

#### shRNA transfection

A pLKO system (Sigma-Aldrich) was utilized for lentiviral RNAi-mediated STAT3 protein knockdown. TRC numbers for shRNAs used STAT3 TRCN0000020839, STAT3 TRCN0000020840, STAT3 TRCN0000020842 or pLKO.1 nontargeting (SHC016). Virus was removed from cells after 24-hour incubation. Validation of STAT3 knockdown was performed by Western blot analysis of cells treated identically alongside MTS, tritiated (3H)-thymidine uptake, and apoptosis assays.

#### MTS assay

Cells were seeded at 4,000 cells per well in 96-well plates (Corning) in antibiotic-free medium and treated with drug or lentiviral solution the next day. S31-201 was used to inhibit STAT3 in 811. S31-201 (Selleck Chemicals) inhibits STAT3:STAT3 complex formation and STAT3 DNA-binding and transcriptional activity and in the original paper inhibited the growth of breast cancer *in vivo* (11). Cell viability was measured using the MTS assay with CellTiter 96 Aqueous One Solution Reagent (Promega) following the manufacturer's protocol 72 hours after drug treatment or 5 days after virus removal. Optical density of each well was measured with a Synergy 2 microplate reader (Biotek) at 490 nm. The proportion of cells per treatment group was normalized to control wells of DMSO control-treated cells or sh nontargeting (NT) control.

#### 3H-thymidine uptake

Cell proliferation as determined by rate of DNA synthesis was measured by 3H-thymidine incorporation. Cells were plated in 96-well plates and treated with a dose range of S31-201 in triplicate as described above. Twenty hours after treatment, each well was pulsed with 0.5 mCi 3H-thymidine, and the plates were incubated at 37°C for 4 hours before cell harvest. For shRNA transfections, lentivirus was added to cells as above, and 3H-thymidine was added 5 days after virus removal. Wells were washed with PBS, and 6% trichloroacetic acid was added to each well. Wells were washed with 1 mL cold 6% trichloroacetic acid after incubation for 1 hour at 4°C. The acid precipitate was dissolved overnight in 50  $\mu$ L 0.5N NaOH and transferred to scintillation vials containing 3 mL of ScintiSafe-30%. Incorporated radioactivity was measured using a scintillation counter. Mitomycin C blocks proliferation and was used as a negative control for 3H-thymidine incorporation.

#### IncuCyte apoptosis analysis

Cells were transfected with nuclear locating signal mCherry (NLS-mCh) virus and antibiotic selected for NLS-mCh<sup>+</sup> cells. Cells were seeded at 4,000 cells per well in 96-well plates in media. Cells were cultured at 37°C and 5% CO<sub>2</sub> and monitored using an IncuCyte Zoom (Essen BioScience). CellEvent Caspase-3/7 Green Detection Reagent (Life Technologies) was added the next day, and baseline images were taken using 10 $\times$  objective. For lentiviral

knockdown, caspase reagent was added following virus removal. S31-201 was added after initial baseline images. Images were captured at 4-hour intervals from 4 separate regions per well using a 10 $\times$  objective over 72 hours. Each experiment was done in triplicate, and accumulation of caspase 3/7 over time was normalized to confluence of cells.

#### Monocyte polarization assays

CD14<sup>+</sup> monocytes were isolated from HLA-matched donor peripheral blood by flow sorting using CD14-FITC (Becton Dickinson) and MoFlo Astrios EQ flow cytometry sorter. Post-sorted cells were incubated in various conditions for 96 hours on ultra-low attachment plates (Corning). 811-conditioned media (811 CM) were collected off 90% confluent 811 cell line and immediately frozen at -80°C for later use. IL6-neutralizing antibody (R&D Systems) was used at concentration of 50  $\mu$ g/mL, and tocilizumab (Genentech) was used at concentration of 1 mg/mL. Media were harvested from cells after 96 hours, and cytokine concentrations were measured by multiplex bead cytokine analysis as described above. Cells were stained with pSTAT3-PE (BD) according to the manufacturer's instructions and run on Beckman Coulter Gallios 561; analysis was done using FlowJo v10.0.7 (FlowJo).

#### IL8 functional assay

Media were harvested from 811-polarized monocytes (MonoCM) or nonpolarized monocytes (MonoO15) as described above. Fresh CD14<sup>+</sup> monocytes were then incubated in MonoCM or MonoO15 for 96 hours. IL8-neutralizing antibody (R&D Systems) was added to MonoCM at 5  $\mu$ g/mL. Cells were collected and myeloid phenotype cell surface markers CD163, HLA-DR, and CD64 were analyzed by flow cytometry as previously described (12). Media were harvested and cytokine concentrations were measured as described above. Cytokine concentrations from primed media were subtracted to assess additional secretion.

#### Statistical analyses

Statistical analyses were performed using R bioinformatics, Prism (GraphPad), and Excel (Microsoft) software. For all tests, statistical significance was defined as  $P < 0.05$ .

## Results

### STAT3-upregulated genes and IL6 signaling pathway genesets are significantly enriched in Group A EPN

We used nonbiased GSEA analysis to identify transcription factor activity that might mechanistically underlie the Group A inflammatory response phenotype. Primary EPN Group A ( $n = 21$ ) and B ( $n = 20$ ) transcriptomic profiles were screened for enrichment of transcriptional programs using MSigDB C3 TFT (transcription factor targets) v.4 motif genesets ( $n = 615$ ) containing genes that share a transcription factor-binding site motif defined in the TRANSFAC database (version 7.4, <http://www.generegulation.com/>). In Group A EPN, transcription factor target genes of leading cancer inflammatory mediator STAT3 (MSigDB: V\$STAT3\_01) were the second most enriched of 615 TFT genesets (NES = 2.07; FDR  $q < 0.0001$ ; Table 1; Supplementary Fig. S2A). Specific STAT3 TFT motif-containing genes highly upregulated (fold change, FC > 10) in Group A include chemokine (C-C motif) ligand 2 (CCL2) and v-maf musculoaponeurotic fibrosarcoma oncogene homolog F (MAFF; Table 2).

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**Table 1.** Enriched genesets in Group A EPN using GSEA analysis<sup>a</sup>

Name	NES	NOM P	FDR q	FWER P
<b>MSigDB C3: motif genesets: transcription factor targets</b>				
GGGNNTTCC_V\$NFKB_Q6_01	2.16	<0.0001	<0.0001	<0.0001
V\$STAT3_01	2.06	<0.0001	<0.0001	<0.0001
V\$NFKAPPAB_01	1.99	<0.0001	0.000468	0.001
TGASTMAGC_V\$NFE2_01	1.96	<0.0001	0.000351	0.001
V\$SRF_01	1.93	<0.0001	0.000281	0.001
V\$NFKB_Q6_01	1.93	<0.0001	0.000234	0.001
V\$NFKB_C	1.92	<0.0001	0.000201	0.001
V\$PEA3_Q6	1.90	<0.0001	0.000176	0.001
V\$CREL_01	1.90	<0.0001	0.000156	0.001
V\$API_Q4	1.89	<0.0001	0.000140	0.001
<b>Experimentally determined STAT3 geneset</b>				
STAT3-upregulated (Yu et al., ref. 13)	2.33	<0.0001	<0.0001	<0.0001
<b>MSigDB C2: curated genesets: BioCarta</b>				
BIOCARTA_NKT_PATHWAY	1.97	<0.0001	0.00684	0.00400
BIOCARTA_INFLAM_PATHWAY	1.95	<0.0001	0.00342	0.00400
BIOCARTA_PML_PATHWAY	1.92	<0.0001	0.00290	0.00500
BIOCARTA_LAIR_PATHWAY	1.86	<0.0001	0.0124	0.0270
BIOCARTA_KERATINOCYTE_PATHWAY	1.83	0.00338	0.0191	0.0540
BIOCARTA_COMP_PATHWAY	1.82	<0.0001	0.0168	0.0570
BIOCARTA_IL2RB_PATHWAY	1.82	0.00166	0.0146	0.0570
BIOCARTA_CDMAC_PATHWAY	1.82	<0.0001	0.0149	0.0660
BIOCARTA_IL6_PATHWAY	1.81	<0.0001	0.0155	0.0770
BIOCARTA_NFKB_PATHWAY	1.80	0.00337	0.0158	0.0870

Abbreviations: FWER, family-wise error rate; NOM, nominal.

<sup>a</sup>The top 10 enriched genesets as ranked by NES are shown for transcription factor target motif and BioCarta genesets.

We further characterized the involvement of STAT3 in Group A EPN by using GSEA to measure enrichment of experimentally determined STAT3-upregulated geneset ( $n = 36$ ), created from a review of the role of STAT3 in cancer inflammation and immunity (ref. 13; Supplementary Table S1). This geneset was enriched in Group A to a greater extent (NES = 2.33; FDR  $q < 0.001$ ) than the STAT3 TFT geneset (Table 1; Supplementary Fig. S2B). Experimentally determined STAT3-upregulated genes in Group A (Table 2) were largely discrete from those identified as STAT3 TFTs with the exception of *CCL2* and *ICAM1*. Notable STAT3-upregulated genes (FC > 10) in Group A include chitinase 3-like 1 (*CH13L1*, AKA *YKL-40*), *IL8*, *CCL2*, *SOCS3*, *IL6*, and prostaglandin-endoperoxide synthase 2 (*PTGS2*, AKA *COX-2*). Collectively, these data suggest activation of the STAT3 signaling pathway in Group A EPN.

It is known that *IL6* drives oncogenic activation of STAT3, increasing cell proliferation, survival, and invasion while suppressing antitumor immunity (13). Persistent *IL6*/STAT3 pathway activation is involved in various inflammation-associated cancers, most notably colorectal (14), gastric (15), and liver (16) cancers. Given the high level of *IL6* gene expression, we hypothesized that *IL6* may be driving activation of STAT3 in Group A EPN. Enrichment of MSigDB C2 BioCarta pathway v.4–curated genesets ( $n = 217$ ; <http://www.biocarta.com/genes/index.asp>) was assessed using GSEA and showed that, in agreement with our hypothesis, the BioCarta *IL6* pathway geneset was among the 10 highest enriched pathways in Group A (NES = 1.81; FDR  $q = 0.015$ ; Tables 1 and 2; Supplementary Fig. S2C). Of note, the BioCarta cytokines and inflammatory response geneset (BIOCARTA\_INFLAM\_PATHWAY) was the second most enriched BioCarta pathway geneset (NES = 1.95; FDR  $q = 0.0034$ ; Supplementary Fig. S2D).

A broader examination of Group A EPN-associated *IL6*/STAT3 pathway genes identified by GSEA gene expression was next performed in EPN from recurrences and supratentorial sites, as well as other common pediatric and adult brain tumors and

normal brain. Recurrent Group A EPN showed reduced expression of *IL6*, consistent with the decreased inflammatory phenotype observed at recurrence that was previously identified (3). *IL6* expression was significantly higher in primary Group A EPN than in all other brain tumor types (Fig. 1A). *IL6* expression was higher in Group A EPN than in both adult GBM (FC = 7.0;  $P = 0.039$ ) and MED (FC = 16.5;  $P = 2.5 \times 10^{-6}$ ), which is notable as constitutive *IL6*/STAT3 activation has been identified in these tumor types (17, 18).

Similar to *IL6*, *IL8* was significantly overexpressed compared with recurrent Group A EPN (FC = 7.6,  $P = 0.0016$ ), with all other brain tumor types (FC = 22-fold higher than all other tumor samples combined;  $P = 4.3 \times 10^{-11}$ ), and with normal brain [(NB) FC = 104;  $P = 1.4 \times 10^{-13}$ ; Fig. 1B]. Thus, overexpression of key inflammatory mediators *IL6* and *IL8* appears to be hallmarks of the Group A EPN transcriptome in the context of not only EPNs as a whole, but of all brain tumors. The apparent restriction of *IL6* and *IL8* gene expression to Group A EPN in this broad transcriptomic analysis provides further evidence that an *IL6*/STAT3 signaling pathway underlies the inflammatory signaling pathway present in Group A EPN.

#### Key Group A EPN *IL6*/STAT3 inflammation signature genes are differentially distributed between tumor and tumor-infiltrating myeloid cells

Prior studies of EPN immunobiology have identified that tumor-infiltrating immune cells can significantly contribute to the overall gene expression profiles of surgical tumor samples (19). A subset of genes associated with longer progression-free survival in EPN were found to be restricted to tumor-infiltrating myeloid cells that contribute up to 25% of the cellular content of surgical tumor specimens (12). The contribution of tumor-infiltrating myeloid cells to the inflammatory TME, through the *IL6*/STAT3 activation, is well established (13, 20). We, therefore, sought to determine the contribution of tumor-infiltrating

**Table 2.** Significantly upregulated genes in Group A EPN from enriched STAT3 and IL6 pathway genesets

Gene symbol	Gene title	FC	P	q
<b>MSigDB C3: motif genesets: transcription factor targets: V\$STAT3_O1 genes</b>				
<i>CCL2</i>	Chemokine (C-C motif) ligand 2	21.62	1.39E-08	3.67E-06
<i>IRF1</i>	Interferon regulatory factor 1	8.66	8.48E-08	1.11E-05
<i>ICAM1</i>	Intercellular adhesion molecule 1	8.32	2.11E-07	2.00E-05
<i>MAFF</i>	v-maf musculoaponeurotic fibrosarcoma oncogene homolog F (avian)	15.87	7.78E-07	5.19E-05
<i>SERPING1</i>	Serpin peptidase inhibitor, clade G (C1 inhibitor), member 1	3.11	6.45E-06	0.000264
<i>CISH</i>	Cytokine inducible SH2-containing protein	2.24	2.45E-05	0.000737
<i>APBA1</i>	Amyloid beta (A4) precursor protein-binding, family A, member 1	1.93	0.00496	0.0393
<b>Experimentally determined STAT3-upregulated genes (Yu et al., ref. 13)</b>				
<i>IL8</i>	Interleukin 8	24.13	5.22E-09	2.17E-06
<i>CCL2</i>	Chemokine (C-C motif) ligand 2	21.62	1.39E-08	3.67E-06
<i>SOCS3</i>	Suppressor of cytokine signaling 3	14.61	1.88E-08	4.35E-06
<i>TIMP1</i>	TIMP metalloproteinase inhibitor 1	5.49	3.65E-08	6.76E-06
<i>ICAM1</i>	Intercellular adhesion molecule 1	8.32	2.11E-07	2E-05
<i>CHI3L1</i>	Chitinase 3-like 1 (cartilage glycoprotein-39); YKL-40	40.27	2.87E-07	2.51E-05
<i>VEGFA</i>	Vascular endothelial growth factor A	4.71	9.77E-07	6.07E-05
<i>PTGS2</i>	Prostaglandin-endoperoxide synthase 2 (prostaglandin G/H synthase and cyclooxygenase); COX-2	10.57	2.82E-06	0.000142
<i>STAT3</i>	Signal transducer and activator of transcription 3 (acute-phase response factor)	1.63	3.72E-06	0.000176
<i>MCL1</i>	Myeloid cell leukemia sequence 1 (BCL2-related)	1.65	7.74E-06	0.00031
<i>VIM</i>	Vimentin	1.41	8.05E-06	0.000318
<i>IL6</i>	Interleukin 6 (interferon, beta 2)	13.41	1.02E-05	0.000381
<i>BIRC3</i>	Baculoviral IAP repeat-containing 3	5.94	6.29E-05	0.001533
<i>MMP9</i>	Matrix metalloproteinase 9 (gelatinase B, 92-kDa gelatinase, 92-kDa type IV collagenase)	7.96	6.32E-05	0.00154
<i>JAK3</i>	Janus kinase 3	3.56	6.54E-05	0.00157
<i>CXCL10</i>	Chemokine (C-X-C motif) ligand 10	7.40	0.000143	0.00281
<i>LIF</i>	Leukemia inhibitory factor (cholinergic differentiation factor)	3.88	0.000153	0.00298
<i>MMP2</i>	Matrix metalloproteinase 2 (gelatinase A, 72-kDa gelatinase, 72-kDa type IV collagenase)	2.59	0.00111	0.0134
<i>CCL5</i>	Chemokine (C-C motif) ligand 5	2.28	0.00405	0.0340
<i>MYC</i>	v-myc myelocytomatosis viral oncogene homolog (avian)	2.09	0.00414	0.0345
<i>IL1B</i>	Interleukin 1, beta	3.10	0.0064	0.0474
<b>MSigDB C2: curated genesets: BioCarta: IL6_PATHWAY genes</b>				
<i>MAP2K1</i>	Mitogen-activated protein kinase kinase 1	1.80	3.65E-06	0.000174
<i>STAT3</i>	Signal transducer and activator of transcription 3 (acute-phase response factor)	1.63	3.72E-06	0.000176
<i>SHC1</i>	SHC (Src homology 2 domain containing) transforming protein 1	2.51	5.35E-06	0.000226
<i>IL6</i>	Interleukin 6 (interferon, beta 2)	13.41	1.02E-05	0.000381
<i>CEBPB</i>	CCAAT/enhancer binding protein (C/EBP), beta	2.01	4.38E-05	0.00114
<i>JAK3</i>	Janus kinase 3	3.56	6.54E-05	0.00157
<i>ELK1</i>	ELK1, member of ETS oncogene family	1.42	0.000123	0.00251
<i>SRF</i>	Serum response factor (c-fos serum response element-binding transcription factor)	1.77	0.000234	0.00409
<i>MAPK3</i>	Mitogen-activated protein kinase 3	1.53	0.000782	0.0104
<i>JUN</i>	jun proto-oncogene	1.70	0.000952	0.0120
<i>FOS</i>	FBJ murine osteosarcoma viral oncogene homolog	3.99	0.00140	0.0159

myeloid cells to the Group A EPN *IL6/STAT3* gene expression signature. Surgical samples from two posterior fossa EPNs were disaggregated and flow-sorted to isolate myeloid cells (CD45<sup>+</sup>, CD11b<sup>+</sup>) and tumor cells (CD45<sup>-</sup>). Transcriptomic analysis was performed, and the relative expression of Group A *IL6/STAT3* inflammation signature genes between these TME cellular compartments was measured (Supplementary Fig. S3). Of the 34 genes identified by GSEA as enriched in the STAT3 TFT, STAT3-upregulated and IL6 pathway genesets (Table 2), *IL8*, *ICAM1*, *PTGS2*, and *IL1B* were on average more than 10-fold higher in the myeloid than in the tumor cell compartments. Conversely, *CHI3L1* gene expression was 67-fold higher in the tumor compartment. *CHI3L1* has a proposed role in driving the Group A EPN-specific mesenchymal phenotype (2). Thus, tumor-infiltrating myeloid cells contribute to the *IL6/STAT3* inflammatory gene expression signature in the Group A EPN.

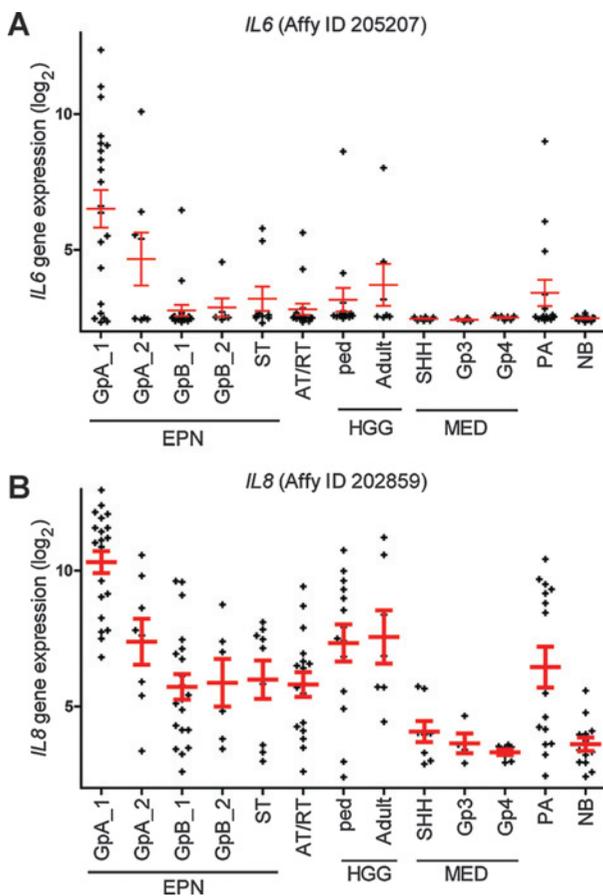
#### Tumor cell secretion of IL6 is associated with STAT3 phosphorylation in Group A EPN

We isolated viable tumor cells, excluding other cells in the TME, from EPN clinical samples (7 Group A; 8 Group B) by tissue

disaggregation and flow sorting to remove all immune cell types as described above. Tumor cells were cultured in 1 mL serum-supplemented media (O15) for 96 hours. Multiplexed cytokine profiling revealed that IL6 was the only cytokine that was significantly higher in Group A versus Group B EPN (FC = 3.5; *P* = 0.031; Fig. 2A). Of the remaining cytokines, only IL10 was >2-fold higher in Group A than in Group B with a trend toward significance (*P* = 0.12; Supplementary Fig. S4).

Presence of significantly higher *STAT3* transcripts and *STAT3*-regulated transcripts is evidence of *STAT3* activity; hence, we evaluated *STAT3* phosphorylation as a more direct indicator of *STAT3* activity in EPN patient samples. Phosphorylation of *STAT3*-Tyrosine 705 by upstream signaling results in dimerization and translocation to the nucleus, resulting in transcription of *STAT3*-target genes. The ratio of tyrosine 705-phosphorylated (p*STAT3*) to total *STAT3* protein, as measured by Western blot analysis, was used as a measure of *STAT3* activity in patient tumor samples (12 Group A; 12 Group B; Fig. 2B shows a representative blot). Densitometric quantification of p*STAT3* and total *STAT3* revealed a significantly higher ratio of phosphorylation in Group A (FC = 1.84; *P* = 0.011; Fig. 2C).

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**Figure 1.**

Key inflammatory cytokine genes *IL6* and *IL8* are upregulated in Group A EPN versus a broad range of brain tumors and normal brain tissues. A, *IL6* and B, *IL8* in Group A EPN compared with recurrent EPN specimens, other pediatric and adult brain tumors, and normal brain tissues. Gp3, Group 3; GrpA, Group A EPN (GpA\_2 and GpB\_2 are first recurrences); ped, pediatric; SHH, sonic hedgehog; ST, supratentorial.

### Constitutively activated STAT3 in EPN has pro-proliferative and antiapoptotic roles

Having identified a potentially critical role for constitutively activated STAT3 in EPN, we examined proliferation and survival of EPN cells after loss of STAT3. Functional studies were performed using an EPN cell line that was recently established from

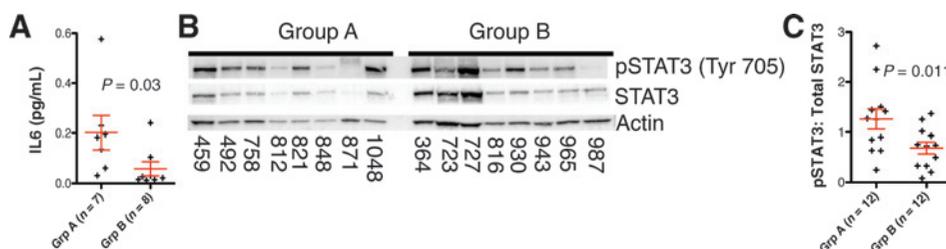
the fourth recurrence in a child with metastatic posterior fossa anaplastic EPN that exhibited a Group A phenotype. This cell line (811) was validated by karyotype analysis and was shown to harbor chromosome 1q-gain (1q<sup>+</sup>), a known poor risk factor for EPN (21). Characterization of these EPN cells demonstrated that 811 secreted comparable amounts of IL6 as secreted by GBM cell line U87, in which aberrant IL6/STAT3 pathway activation had previously been identified and associated with invasiveness (ref. 22; Fig. 3A).

Loss of STAT3 through shRNA knockdown (Fig. 3B) resulted in significant reduction in proliferation of 811 cells than NT control shRNA (shNT) as measured by both cell-viability measurement (MTS) and DNA synthesis (3H-thymidine; Fig. 3C and D). Pharmacologic STAT3 inhibition (S3I-201) showed that 811 cells were more sensitive (viability IC<sub>50</sub> = 108 μmol/L; DNA synthesis IC<sub>50</sub> = 86 μmol/L) than U87 cells (viability IC<sub>50</sub> = 140 μmol/L; DNA synthesis IC<sub>50</sub> = 225 μmol/L; Supplementary Fig. S5A and S5B). The clinical relevance of these S3I-201 IC<sub>50</sub> values is unknown, as S3I-201 has not yet been tested in a clinical trial, rather this inhibitor provides proof-of-principle for therapeutic targeting of STAT3. STAT3 inhibition did not affect cell cycle in 811 cells (Supplementary Fig. S5C). However, shRNA knockdown of STAT3 resulted in activation of apoptosis, with significant increase of cleaved caspase 3/7 compared with shNT (Fig. 3E), and significant apoptosis was demonstrated using S3I-201 at >IC<sub>50</sub> concentration (Supplementary Fig. S5D). Collectively, these data support the hypothesis that, in EPN with constitutively activated STAT3, this transcription factor has both prosurvival and antiapoptotic roles.

We observed an S3I-201 dose-dependent reduction of pSTAT3 pathway protein levels by Western blot (Supplementary Fig. S5E). Although total STAT3 remained relatively constant up to 500 μmol/L of S3I-201, phosphorylation was completely inhibited above 125 μmol/L. STAT3 transcriptional targets SOCS3 and MCL-1 were similarly reduced in a dose-dependent manner. STAT3 inhibition did not, however, reduce secretion of IL6, suggesting that IL6 regulation is upstream of STAT3 in the signaling pathway (Fig. 3F; Supplementary Fig. S5F).

### EPN-secreted IL6 induces CD14<sup>+</sup> monocytes to secrete key proinflammatory cytokine IL8

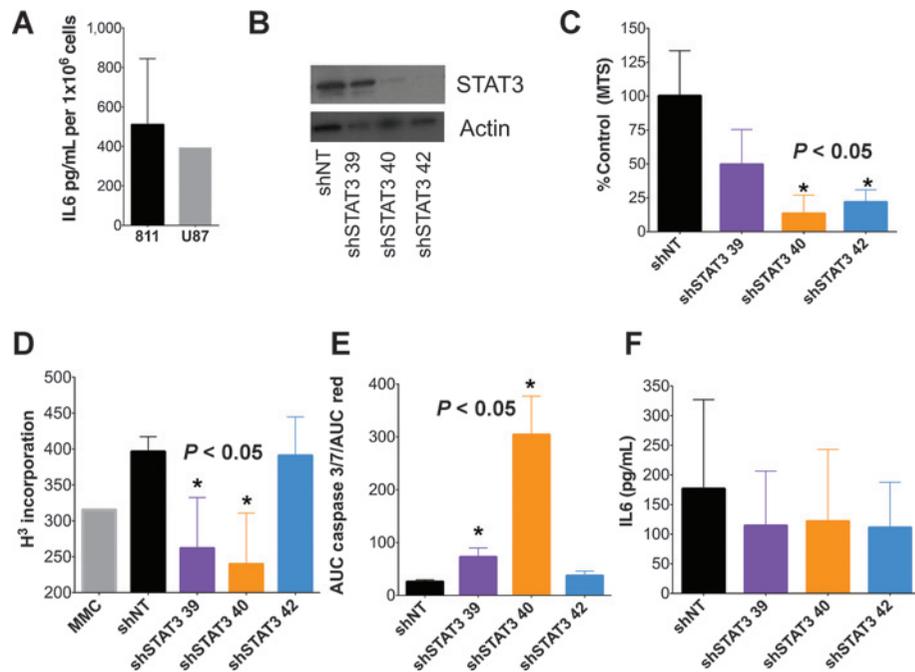
Transcriptomic analyses of Group A EPN identified that tumor-infiltrating myeloid cells contributed strongly to the inflammatory phenotype, and specifically *IL8* expression, a hallmark of the IL6/STAT3 inflammation signature geneset, was highly enriched

**Figure 2.**

Group A EPN patients have higher levels of IL6 production and a higher ratio of pSTAT3 than Group B patients. A, concentration of IL6 secretion from flow-sorted disaggregated tumor samples is higher in group A (FC = 3.5;  $P = 0.031$ , 1-tailed  $t$  test). Cells were cultured for 96 hours in O15 and normalized to  $10^6$  cells. B, representative Western blot showing expression of pSTAT3 and total STAT3 in patient samples. C, Western blot validation of pSTAT3 activation in surgical samples from 12 Group A and 12 Group B EPN patients. The ratio of pSTAT3 to total STAT3 was determined by densitometric measurement of Western blot bands. This demonstrated a higher ratio of STAT3 phosphorylation in samples from Group A EPN patients (FC = 1.84;  $P = 0.012$ ).

**Figure 3.**

EPN cell line 811 is sensitive to STAT3 knockdown leading to apoptosis. A, concentration of IL6 secretion from newly created pediatric EPN cell lines and control GBM cell line. B, Western blot validation of STAT3 knockdown in 811 cell line (representative blot). All experiments using shRNA knockdown were validated by Western blots. C and D, inhibition of cell proliferation by STAT3 knockdown was assessed by MTS and <sup>3</sup>H-thymidine incorporation in 811 cells. Graphs are representative experiments. MMC, mitomycin C. E, real-time quantification of cleaved Caspase 3/7, representative of apoptosis, over 160 hours of STAT3 knockdown. Graph shows accumulation of cleaved caspase 3/7 normalized to cell numbers. F, IL6 secretion by 811 cells after STAT3 knockdown. \*, *P* < 0.05 calculated using 2-tailed paired *t* test.



in tumor-infiltrating myeloid cells (Supplementary Fig. S3). By multiplex cytokine analysis, IL6 was the predominant cytokine secreted by 811 cells, being 55-fold higher than IL8, the next highest-secreted cytokine (Supplementary Fig. S6A). No other cytokines were detected apart from trace amounts of GM-CSF, IFN $\gamma$ , IL13, and IL7 (Supplementary Fig. S6A).

We hypothesized that IL6 secreted at high levels by EPN in the TME polarize tumor-infiltrating myeloid cells to an inflammatory phenotype in a paracrine fashion, resulting in activation of myeloid cell STAT3 and upregulation of transcriptional targets, including IL8. To evaluate this, CD14<sup>+</sup> monocytes were isolated from tumor HLA-matched peripheral blood mononuclear cells by flow sorting and were immediately cultured in 250  $\mu$ L of either (i) 811CM, or (ii) O15 control media, for 96 hours. Supernatant from the CD14<sup>+</sup> monocyte cultures was then subject to multiplex cytokine analysis. Background cytokine levels in CM were subtracted from CD14<sup>+</sup> monocyte/CM culture cytokine levels to identify changes in monocyte-derived cytokines. There was a 9.2-fold increase (*P* = 0.043) in IL8 secretion from CD14<sup>+</sup> cells treated with 811CM compared with that with media control alone (Fig. 4A). The remaining 12 cytokines tested did not show any significant differences (data not shown).

To determine whether IL8 production in CD14<sup>+</sup> monocytes was induced by EPN-derived IL6, the experiment was repeated with the addition of IL6-neutralizing antibody (IL6NA) or IL6 receptor-neutralizing antibody tocilizumab. In both cases, production of IL8 by monocytes was significantly lowered by greater than 75% (Fig. 4B). Furthermore, flow cytometric measurement of pSTAT3 demonstrated significant induction of STAT3 phosphorylation (Tyr-705) in CD14<sup>+</sup> monocytes, and this was reversed with addition of IL6NA (Fig. 4C and D). EGF, a potential alternative activator of STAT3, was shown not to drive STAT3 phosphorylation or IL8 release, as EGFR-blocking antibody cetuximab did not reverse this phenotype in 811 CM-treated myeloid

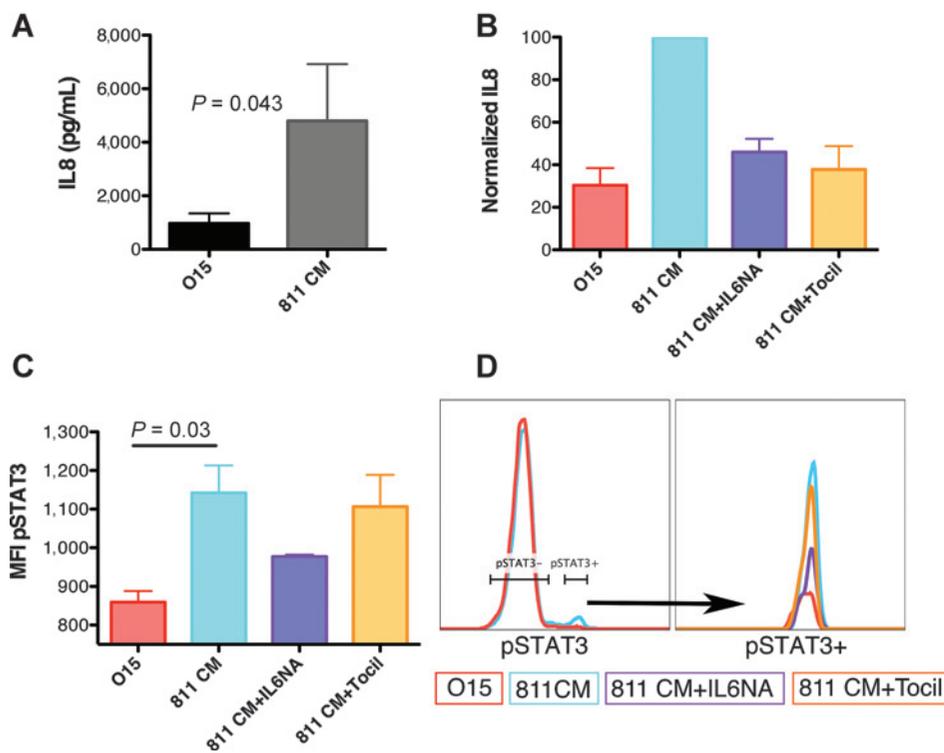
cells (Supplementary Fig. S6B and S6C). Together, these data support our hypothesis that Group A EPN secretes IL6, which stimulates production of proinflammatory IL8 by myeloid cells via activation of STAT3 in the TME in a paracrine fashion.

#### IL8-mediated signaling between monocytes perpetuates inflammatory signaling in the TME

IL8 is a potent chemokine that has a variety of roles in inflammation. Although its most common function is to induce neutrophil infiltration, IL8 can also promote tumor-associated macrophages to secrete more cytokines and growth factors that further induce proliferation and tumor invasion (23). IL8 was the only cytokine we found to be significantly upregulated by monocytes in response to tumor cell paracrine signaling (Fig. 4A). We hypothesized that IL8 production by tumor-polarized monocyte could further polarize monocytes in a paracrine fashion. To test this hypothesis, freshly sorted CD14<sup>+</sup> monocytes were cultured in media harvested from CD14<sup>+</sup> monocytes that had been primed in either tumor-conditioned media (MonoCM) or control media (MonoO15) for 96 hours. Strikingly, a significant upregulation of CD163 was observed in cells cultured in MonoCM compared with those cultured in control media (Fig. 5A). In addition, MonoCM induced secretion of a number of common proinflammatory cytokines IL10, IL13, IL1 $\beta$ , IL6, IL7, and IL8 (Fig. 5B). Addition of IL8-neutralizing antibody to MonoCM prevented CD163 upregulation and was accompanied with upregulation of both HLA-DR and Fc-receptor CD64 expression (Fig. 5A). All proinflammatory cytokine production was reduced with the addition of IL8-neutralizing antibody to MonoCM (Fig. 5B).

Collectively, these studies provide evidence that EPN tumor cells induce paracrine polarization of monocytes through secretion of IL6. This inflammatory phenotype is then amplified between monocytes through upregulated IL8 production.

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**Figure 4.** EPN cell line 811 can induce immunosuppressive phenotype in HLA-matched donor CD14<sup>+</sup> peripheral blood mononuclear cells. A, IL8 secretion from HLA-matched donor CD14<sup>+</sup> monocytes incubated for 96 hours in either control media (O15) or media collected from 811 cell line (811 CM). IL8 concentration in pg/mL per 30,000 cells in 250 mL. Experiments were completed in triplicate. *P* value calculated using 1-tailed *t* test. B, IL8 secretion from CD14<sup>+</sup> monocytes incubated for 96 hours in O15, 811 CM, 811 CM plus 50  $\mu$ g/mL IL6-neutralizing Ab (811 CM + IL6NA), 811 CM plus 100  $\mu$ g/mL tocilizumab (811 CM + Tocil). Experiments were run in triplicate and normalized to 811 CM-cultured monocytes for each experiment. C, median fluorescence intensity (MFI) of pSTAT3 from CD14<sup>+</sup> monocytes incubated. Representative flow plot of (left) pSTAT3 for 811CM and control-treated CD14<sup>+</sup> monocytes, and (right) representative flow plot of pSTAT3-positive peak in all treatment conditions. *P* value calculated using a 1-tailed *t* test.

## Discussion

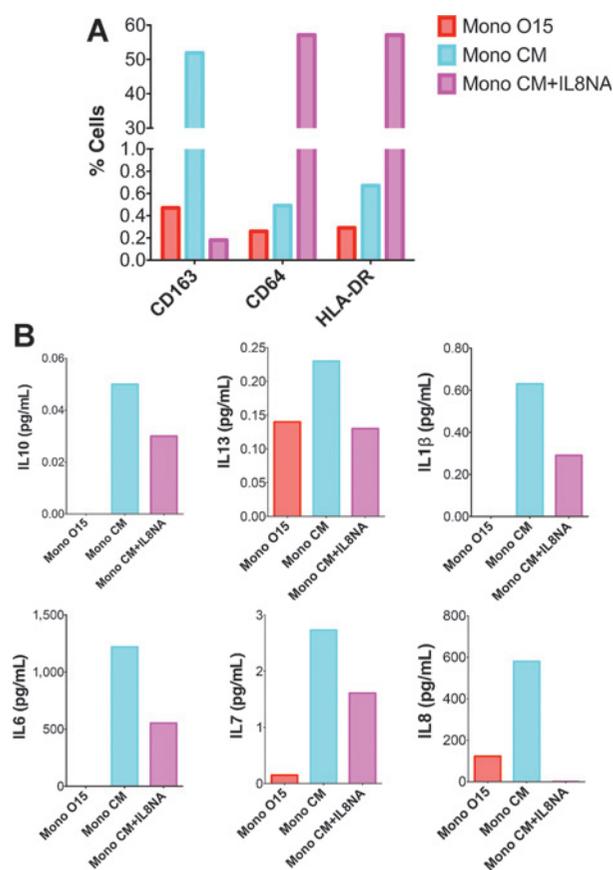
Inflammatory response has been identified as a predominant transcriptomic phenotype in Group A EPN (1–3). The present study identifies tumor IL6/STAT3 pathway activation and cross-talk with myeloid cells as a potential mechanism underlying this phenotype. IL6/STAT3-mediated cross-talk between tumor and immune cells, resulting in inflammation, has been well documented in a number of tumors (20). Persistent IL6/STAT3 pathway activation is involved in various inflammation-associated cancers, most notably colorectal (14), gastric (15), and liver (16) cancers. It is known that oncogenic activation of STAT3, driven by IL6, increases cell proliferation, survival, and invasion as well as suppressing antitumor immunity (13). Tumor-derived IL6 affects the differentiation of myeloid lineages, including macrophages and dendritic cells, through STAT3 activation in these immune cell types (24). STAT3 activation in tumor-associated myeloid cells results in expression of proinflammatory mediators and upregulation of angiogenic factors and growth factors, leading to increased tumor growth in a paracrine fashion (20). In this study, EPN tumor cells were shown to release IL6, which activated myeloid cell STAT3 in a paracrine fashion. STAT3 activation resulted in increased IL8 production, which further polarizes myeloid cells to an inflammatory phenotype.

In the central nervous system, oncogenic IL6/STAT3 signaling has been documented predominantly in GBM, the most common malignant brain tumor in adults, as important in proliferation, survival, and invasiveness of tumor cells and as a key regulator of the immunosuppressive microenvironment (25–29). GBM have been demonstrated to harbor protumor microglia/macrophages that are polarized by glioma stem cell–secreted factors (30). This cross-talk has been attributed to STAT3 activation (31). Therapeutic

targeting of STAT3 has also shown promise in the most common malignant pediatric brain tumor, MED (17, 32). To our knowledge, the present study represents the only demonstration of such cross-talk in EPN. Given that *IL6* and *IL8* gene expression is elevated in Group A EPN when compared with other brain tumors, including GBM and MED, it emphasizes the particular importance of IL6/STAT3 signaling and immune cross-talk in the biology of this tumor.

The EPN Group A IL6/STAT3 activation geneset includes critical effectors of the key phenotypic characteristics of Group A EPN (1–3), namely inflammation [*IL8*, *CCL2*, *PTGS2* (*COX2*)], mesenchymal transition (*CHI3L1*), invasiveness (*TIMP1*, *MMP2*, *MMP9*), angiogenesis (*VEGFA*), and antiapoptosis (*MCCL1*, *BIRC3*). Thus, constitutive IL6/STAT3 signaling may underlie a number of the characteristic oncogenic phenotypes of Group A EPN, representing a "molecular hub" as has previously been ascribed to STAT3 in gliomas (33). A recent epigenomic study of EPN revealed that Group A, unlike Group B, exhibits a CpG island methylator phenotype (CIMP), suggesting epigenetic modifiers as rational therapeutic candidates in this molecular subgroup (34). Both IL6 and STAT3 have been shown to drive hypermethylation, potentially linking the IL6/STAT3 pathway with CIMP in this subgroup (35–37). Given these potentially pivotal roles of IL6/STAT3 in Group A EPN tumor biology, therapeutic exploration of STAT3 and/or IL6 inhibition is warranted.

We have previously shown that immunity affects outcome in pediatric EPN (19). Subsequently, we characterized immunologic differences in posterior fossa EPN, identifying an immunosuppressed phenotype in Group A when compared with Group B (3). Specifically, T cells derived from Group A tumors did not respond to stimulation with appropriate cytokine release and appeared to



**Figure 5.**

IL8 secreted by EPN-polarized macrophages induces further M2-like polarization of monocytes. CD14<sup>+</sup> monocytes were incubated in O15 or 811 CM as previously described in Fig. 4. Media were then used to incubate another set of CD14<sup>+</sup> monocytes (MonoO15, MonoCM). IL8-neutralizing antibody (MonoCM+IL8NA) was used at 5 μg/mL. A, flow cytometry evaluation of cell surface markers on CD14<sup>+</sup> monocytes after incubation in media collected from EPN tumor-primed monocytes. Graphs are percentage myeloid cells. B, concentration of cytokines secreted by monocytes from A. Cytokine already present in the media from initial polarization was subtracted to reflect additional cytokine production in pg/mL.

have an exhausted phenotype compared with those derived from Group B tumors, a finding also seen in GBM (38). Thus, in Group A EPN, there is an association of IL6/STAT3-mediated inflammation with an immunosuppressed phenotype. Numerous mechanisms have been demonstrated to link inflammation to immunosuppression, such as generation of myeloid-derived suppressive cells (39) and immunosuppressive T-cell subsets (40). STAT3 has been shown to inhibit expression of antitumor T<sub>H</sub>1-type immune-stimulating molecules, and promote expression of immunosuppressive factors, and is therefore likely drives immunosuppression in Group A EPN (41). With the recent success of

cancer therapies that inhibit immunosuppressive factors, most notably CTLA-4 and PD-1 (42, 43), identification of a tumor-associated myeloid cell-mediated immunosuppressive mechanism in Group A EPN has particular clinical relevance. Reversal of myeloid cell-mediated immunosuppressive phenotypes for therapeutic gain has been achieved by T-cell activation strategies, such as IL12 treatment that results in reprogramming of tumor-associated myeloid cells (44). Alternatively, directly targeting tumor-associated myeloid cells has shown promise, as achieved by CSF-1R inhibition in GBM (45). The ability of IL6 receptor antagonist tocilizumab, which is FDA approved for treatment of rheumatoid arthritis (46), to abrogate IL6/STAT3-mediated tumor/myeloid cell cross-talk in the present study provides yet another therapeutic approach. Group A EPN has a poor outcome and little evidence that it is responsive to standard chemotherapy. Our work is highly suggestive that in the realm of pediatric brain tumors, this specific subgroup of EPN would be a strong candidate for the development of immunotherapy.

#### Disclosure of Potential Conflicts of Interest

R. Vibhakar reports receiving commercial research support from Epizyme. No potential conflicts of interest were disclosed by the other authors.

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**Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.):** A.M. Griesinger, A.M. Donson, J.M.M. Levy, V. Amani, L.M. Hoffman, R. Vibhakar, N.K. Foreman

**Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis):** A.M. Griesinger, A.M. Donson, J.M.M. Levy, D.K. Birks, R. Vibhakar, N.K. Foreman

**Writing, review, and/or revision of the manuscript:** A.M. Griesinger, A.M. Donson, J.M.M. Levy, L.M. Hoffman, S.L. Furtek, P. Reigan, M.H. Handler, N.K. Foreman

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