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GM-CSF Production by Glioblastoma Cells Has a Functional Role in Eosinophil Survival, Activation, and Growth Factor Production for Enhanced Tumor Cell Proliferation

Colleen S. Curran,* Michael D. Evans,† and Paul J. Bertics*‡

Medicinal interventions of limited efficacy are currently available for the treatment of glioblastoma multiforme (GBM), the most common and lethal primary brain tumor in adults. The eosinophil is a pivotal immune cell in the pathobiology of atopic disease that may form in response to chronic inflammation or promote inflammatory responses associated with cancer and asthma. Blood and tissue eosinophils are now extensively reported in many types of human cancers (4, 5) and are well established contributors to the pathology of asthma and allergy (6). Cancer may form in response to chronic inflammation or promote inflammation through the activation of oncogenes (7). Although the role of eosinophils in these processes is not yet clear, eosinophil recruitment to the tumor microenvironment has been indicated to occur in response to necrosis, tumor-secreted IL-5, IgE Abs, and therapeutic treatment with IL-2, IL-4, or GM-CSF (5, 8–10). In asthma, the immune response has been characterized by early-phase IgE-mediated activation of mast cells, the production of proinflammatory cytokines (e.g., IL-2, IL-4, IL-5, GM-CSF), and the late-phase recruitment of Th2 cells and eosinophils (11). Evidence of an inverse relationship between atopic disease and the development of a particular cancer, glioblastoma (12–15), suggests that the eosinophil or eosinophilic mediators, or both, may play a pivotal role in an anticancer response.

Glioblastoma multiforme (GBM) is the most common and lethal primary brain tumor in adults despite the available cancer treatments of surgical resection, radiotherapy, and chemotherapy (16). Glioblastoma tumor cells are reportedly able to evade surgical, radiotherapeutic, chemotherapeutic, and immunotherapeutic interventions by respectively infiltrating into the surrounding brain tissue, downregulating tumor-suppressor proteins, upregulating DNA repair enzymes, and producing immunosuppressive cytokines (17). Notably, enhanced glioblastoma patient survival has been correlated with tissue eosinophilia in clinical trials involving postoperative treatments with IL-2 (18, 19). In animal models, transplanted glioblastoma tumor cells that express a high level of IL-2, IL-4, or GM-CSF displayed enhanced survival, reduced tumor growth, and significant eosinophil infiltrate compared with controls (20–22).

Eosinophil recruitment has also been indicated to occur in response to developing subdural hematomas (23), necrotic tissue (24), and radiotherapy (25), conditions known to exist in human primary GBM (16, 26). In patients with allergy and asthma, eosinophil recruitment involves cytokine (IL-3, IL-5, GM-CSF) priming in the peripheral blood that sensitizes eosinophilic adhesion molecules (CD11b/CD18, CD49d/CD29) to more effectively interact with adhesion ligands (ICAM-1, VCAM-1) on the...
inflamed endothelia (27). Whether similar interactions occur in eosinophil recruitment to certain tumors is unclear. Understanding the distinct tumor microenvironments that encourage eosinophil infiltration may lead to more effective treatment parameters. Therefore, the aim of this study was to examine potential paracrine interactions between human primary eosinophils and glioblastoma cells, with a particular focus on the cytokine GM-CSF.

Materials and Methods

**Isolation of peripheral blood eosinophils**

Peripheral blood was obtained from human allergic patients under informed consent. The study was approved by the University of Wisconsin-Madison Center for Health Sciences Human Subjects Committee. Eosinophils were purified from heparinized blood that was diluted with HBSS (Mediatech, Manassas, VA) without Ca²⁺ and centrifuged for 20 min at 700 × g over 1.090 g/ml Percoll. A granulocyte fraction was obtained after removal of the plasma, mononuclear cell band, and Percoll. Granulocytes were then subjected to RBC lysis via hypotonic shock, washed with 4˚C HBSS supplemented with 2% newborn calf serum (Life Technologies Grand Island, NY) and separated 40 min with magnetic beads coated with anti-CD16, anti-CD14, and anti-CD3 (Miltenyi Biotechnology, Aubum, CA) before negative selection with an AutoMACS separator (Miltenyi Biotechnology). The recovered mixture (≥97% purity; ≥98% viability) was evaluated by Giemsa’s-based Diff-Quik stain (Baxter Scientific Products, McGaw Park, IL) and trypan blue exclusion, respectively.

**Cell lines, cell culture, and reagents**

The A172 and U87-MG glioblastoma cell lines were purchased from the American Type Culture Collection (Manassas, VA). The H358 non-small cell lung cancer (NSCLC) and DU145 prostate carcinoma cell lines were kindly provided by Drs. Paul Harari and Wade Bushman (University of Wisconsin, Madison, WI), respectively. Eosinophils and cell lines were cultured in DMEM (Mediatech) supplemented with 2% newborn calf serum (CCS; Hyclone, Logan, UT), 100 U/ml penicillin/streptomycin (Mediatech), and 1% heat-inactivated FBS (Mediatech). The A172 and U87-MG glioblastoma cell lines, with a particular focus on the cytokine GM-CSF.

**Cell lines culture, and reagents**

The A172 and U87-MG glioblastoma cell lines were purchased from the American Type Culture Collection (Manassas, VA). The H358 non-small cell lung cancer (NSCLC) and DU145 prostate carcinoma cell lines were kindly provided by Drs. Paul Harari and Wade Bushman (University of Wisconsin, Madison, WI), respectively. Eosinophils and cell lines were cultured in DMEM (Mediatech) supplemented with 2% newborn calf serum (CCS; Hyclone, Logan, UT), 100 U/ml penicillin/streptomycin (Mediatech) at 37˚C, 5% CO2. Cells were treated with GM-CSF (R&D Systems, Minneapolis, MN), TNF-α (R&D Systems), or dexamethasone (Sigma Chemical, St. Louis, MO).

**ELISA**

Anti-GM-CSF mAbs (clone 6804; 1:1000; R&D Systems) in 0.1 M sodium carbonate buffer, pH 9.6, were coated onto 96-well enzyme immunoassay/radioimmunoassay plates (Costar, Corning, NY). Blocking buffer containing 1% BSA (Sigma Chemical) and 0.5% Tween 20 (Fisher Scientific, Pittsburgh, PA) in PBS was added to wells for 2 h. Serial dilutions of GM-CSF standard (215-GM; R&D Systems) and cell-free supernatants were aliquoted and incubated at 4˚C overnight. GM-CSF was detected with biotinylated GM-CSF Abs (clone 3209; 1:1000; R&D Systems) and subsequent exposure to streptavidin HRP-40 (Fitzgerald Industries International, Concord, MA). A colorimetric HRP substrate tetramethylbenzidine (Biox’s Laboratories, Owings Mills, MD) was used to evaluate captured HRP activity, and the enzymatic reaction was stopped with 0.18 M sulfuric acid. OD was determined on an ELx800 Universal Microplate Reader (BioTek Instruments, Winooski, VT). Absorbance was quantified at 450 nm, using 600 nM as a reference wavelength. GM-CSF concentrations were calculated by interpolation from a standard curve, and all determinations were performed in triplicate.

**Flow cytometric analysis of cell surface molecules**

Tumor cell lines or eosinophils were suspended in 100 μl DMEM containing 1% CCS and treated (1×10⁶ cells) with unconjugated mouse anti-human ICAM-1 Abs (clone BBIG-I1(11C81); R&D systems), FITC-conjugated CD69 Abs (clone FN50; BD Biosciences Pharmingen, San Jose, CA), PE-conjugated CD11b Abs (clone ICRF44; BD Bio
sciences Pharmingen), or isotype control, and incubated for 30 min at 4˚C. Cells were washed with 1 ml 1% CCS DMEM. For analysis of ICAM-1, which involved unconjugated primary Abs, PE goat anti-mouse Abs (Invitrogen, Eugene, OR) were used as a secondary and incubated for 30 min at 4˚C in the dark. Cells were suspended in PBS, treated with propidium iodide (3 μg/ml) to exclude dead cells, and analyzed at 10,000 events/second (Cytoflet-5; Beckton-Dickinson, Bedford, MA) at the University of Wisconsin Comprehensive Cancer Center Flow Cytometry Core Facility. Data were analyzed with FlowJo data analysis software (TreeStar, Ashland, OR).

**Assay of eosinophil peroxidase activity**

Eosinophil adherence was determined by measuring the eosinophil peroxidase (EPO) activity of adherent cells using a modification of the methods previously described (28–30). In triplicate, 100 μl media (10% CCS DMEM) or glioblastoma cells (5 × 10⁵/ml) were added to 96-well tissue culture plates (Sarstedt, Newton, NC). After 24-h incubation, 10 ng/ml TNF-α or buffer control was added to media or glioblastoma cells for an additional 24 h. At the 48-h time point, 100 pg/ml GM-CSF, 10 μg/ml GM-CSF neutralizing Abs (clone BV2D-23B6; Invitrogen), or isotype control Abs were added for 1 h. Eosinophils were suspended in HBSS (Mediatech) and added to the plate in 10-μl aliquots for a final concentration of 1 × 10⁵ eosinophils/ml. Additional eosinophils were saved on ice for use as a standard. After the 96-well plate containing the sample was incubated at 37˚C for 30 min. The plate was washed twice with 200 μl HBSS, and 100 μl HBSS was aliquoted to each well. An eosinophil standard was plated in triplicate (1 × 10⁵ eosinophils/ml) and serially diluted in HBSS. Reaction buffer (100 μl containing 0.1% Triton X-100 (Sigma Chemical), 50 mTrit (pH 8), 1 mM H2O2, and 1 mM O-phenylenediamine dihydrochloride (Sigma Chemical) was added to each well for an additional 30 min. The reaction was stopped with 4 M H2SO4 (50 μl), and OD was measured at 490 nm. The absorbance levels of EPO activity were used as an indirect measurement of eosinophil adherence by subtracting background values and interpolating the relative number of cells adhered from the standard curve.

**Immunofluorescence**

Glioblastoma cells (1 × 10⁵/ml) were labeled with 1 μM Cell Trace CFSE (C34554; Invitrogen-Molecular Probes, Eugene, OR) per manufacturer’s instructions, and plated on coverslips (5 × 10⁵/ml) and incubated at 37˚C. After 24-h incubation, 10 ng/ml TNF-α or buffer control was added to media or glioblastoma cells for an additional 24 h at 37˚C. At the 48h-time point, 100 pg/ml GM-CSF, 10 μg/ml GM-CSF neutralizing Abs (clone BV2D-23B6; Invitrogen) or isotype control Abs were added for 1 h and incubated at 37˚C. Eosinophils (1 × 10⁵/ml) were monocolored or cocultured with glioblastoma cells and incubated 10 min at 37˚C. Media were aspirated and coverslips were washed twice with 1 ml ice-cold PBS (pH 7.4). Cells were fixed in room temperature 4% paraformaldehyde (10 min), permeabilized with PBS containing 0.1% Triton X-100 (10 min; Sigma Chemical), and washed with PBS (5 min) and TBST (pH 8; 5 min). Each coverslip was blocked with TBST containing 1% BSA (Sigma Chemical) and 4% normal donkey serum albumin (Jackson ImmunoResearch Laboratories, West Grove, PA). Cells were immunostained at room temperature with CD11b Abs (clone ICRF44; 1:50, 1 h; R&D Systems), washed three times for 10 min with TBST, and immunostained with DAPI nucleic acid stain (1:10,000; Invitrogen) and Alexa Fluor 594-labeled donkey anti-mouse Abs (1:2000, 1 h; Invitrogen). After washing three times for 10 min with TBST, coverslips were rinsed in dH2O and mounted onto slides with Pro
gold antifade reagent (Invitrogen). Glioblastoma cells and eosinophils were also cultured separately at 48 h and 594 min using a Nikon fluorescence microscope. A total of five images of each coverslip were randomly taken. Eosinophils identified by red CD11b staining and blue DAPI staining from four different donors were counted and averaged.

**Eosinophil viability assay**

Human glioblastoma cells (5 × 10⁵ cells/0.5 ml) were cultured above 150 μl 0.5% w/v LE analytical grade agarose (Promega, Madison, WI), 48-well plate (Sarstedt). At 24 h, 500 μl eosinophils (2 × 10⁵ cells) was added to semisolid glioblastoma spheres for an additional 96 h. In some experiments, GBM cell line-conditioned media (5 × 10⁵ cells/ml) was used as a source of soluble cytokines. Eosinophils were seeded with glioblastoma spheres at 48 h and 594 min using a Nikon fluorescence microscope. A total of five images of each coverslip were randomly taken. Eosinophils identified by red CD11b staining and blue DAPI staining from four different donors were counted and averaged.
Comprehensive Cancer Center Flow Cytometry Core Facility. Data were analyzed with FlowJo data analysis software (TreeStar) as shown in a representative example (Supplemental Fig. 2).

**Immunoblotting**

For an assessment of receptor for advanced glycation end products (RAGE) expression, cells were solubilized with lysis buffer (1% NaDodSO4 [SDS]), 10 mM DTT, 0.5 mM Na3VO4, 1 mM EDTA, 10% glycerol, 10 mM Tris, pH 8.0), sonicated, boiled (5 min), and 50 μg protein, as determined by Micro-BCA protein assay reagents (Thermo Scientific Pierce, Rockford, IL). Media were loaded onto a 10% SDS-PAGE gel. For analysis of S100A9, human primary blood eosinophils (5 × 10^6/ml) were loaded in 96-well tissue-culture plates (Sarstedt) at pH 8.0, sonicated, boiled (5 min), and 50 μg protein, as determined by Micro-BCA protein assay reagents (Thermo Scientific Pierce, Rockford, IL). Media were loaded onto a 10% SDS-PAGE gel. For analysis of S100A9, human primary blood eosinophils (5 × 10^6/ml) were loaded in 96-well tissue-culture plates (Sarstedt) at pH 8.0, sonicated, boiled (5 min), and 50 μg protein, as determined by Micro-BCA protein assay reagents (Thermo Scientific Pierce, Rockford, IL). Media were loaded onto a 10% SDS-PAGE gel.

**MTS assay**

Metabolism of 3-(4,5-dimethylthiazol-2-yl)-5-(3-carboxymethoxyphenyl)-2-(4-sulfophenyl)-2H-tetrazolium (MTS) was used as an index of cell viability. Glioblastoma cell lines (2 × 10^5 cells/ml) were incubated in complete media in 96-well tissue-culture plates (Sarstedt) for 4 h to allow for adherence at 37°C. Media were replaced with serum-free media for 24 h and subsequently replaced with 0.1% CCS DMEM ± 100 pg/ml GM-CSF, 10% CCS DMEM (live control), 10 mM sodium azide (NaN3) in 0.1% CCS DMEM (dead control), or eosinophils-conditioned media obtained from 2 × 10^6/ml eosinophils cultured in 0.1% CCS DMEM (live control) and 10% sodium azide (NaN3) in 0.1% CCS DMEM (dead control). Glioblastoma cell lines were incubated with specified controls or eosinophil-conditioned media for 48 h at 37°C. Each well was aspirated and replaced with 100 μl/well PBS plus 20 μl/well of the CellTiter 96 Non-Radioactive Cell Proliferation Assay component involving MTS (inner salt, 2 mg/ml; G1111; Promega, Madison, WI) and an electron coupling reagent phenazine methosulfate (0.92 mg/ml; P9625; Sigma Chemical). After 1-h incubation at 37°C, the reduction of MTS to EPO assays as an indirect measurement of adherence.

To assess whether the U87-MG cell line induces preferential eosinophil adhesion compared with the A172 cell line, we performed EPO assays as an indirect measurement of adherence. Fig. 2A displays data revealing that eosinophil adherence to both tumor cell

**Statistical analysis**

Analyses in all experiments were assessed among conditions using mixed-effects ANOVA models with a fixed-effect covariate per condition and a random-effect covariate to account for within-patient correlation of measurements. A two-sided p value <0.05 was regarded as statistically significant. The SEM indicates interassay variability.

**Results**

Characterization of glioblastoma cell lines

In allergy and asthma, the cytokine GM-CSF has been indicated to induce the sensitization of eosinophil adhesion molecules (CD11b/CD18, CD49d/CD29) to more effectively interact with their ligands (27). These ligands include ICAM-1, VCAM-1, and possibly RAGE (27, 33). To begin to understand eosinophil recruitment mechanisms in response to tumor cells, we examined the human A172 and U87-MG GBM cell lines for their potential production of GM-CSF and expression of adhesion molecules (ICAM-1, VCAM-1, RAGE). In Fig. 1A, basal levels of GM-CSF production were not detectable with the A172 cells, whereas the U87-MG cells produced >100 pg/ml GM-CSF during the 48-h time span. Addition of TNF-α to the cells enhanced the production of GM-CSF by either cell line, most significantly for the U87-MG cells. Likewise, in Fig. 1B, basal levels of adhesion molecules were not detectable in the A172 cells, whereas ICAM-1 was significantly expressed by the U87-MG cells. Addition of TNF-α to the cells induced ICAM-1 and VCAM-1 expression in the A172 cells but enhanced only ICAM-1 expression in the U87-MG cells. In examining RAGE expression, the A172 and U87-MG cell lines were compared with known positive (DU-145 prostate carcinoma cell line) (34) and negative (H358 NSCLC cell line) (35) controls. Fig. 1C illustrates that both the A172 and U87-MG cell lines express RAGE, and that the U87-MG cells display 5-fold greater levels of this molecule when compared with the A172 cells. These data suggest that in the absence of stimuli, such as TNF-α, the U87-MG cell line may be able to induce stronger eosinophil adhesion responses in culture.

**Eosinophil adherence as measured by EPO activity in response to glioblastoma cocultures**

To assess whether the U87-MG cell line induces preferential eosinophil adhesion compared with the A172 cell line, we performed EPO assays as an indirect measurement of adherence. Fig. 2A displays data revealing that eosinophil adherence to both tumor cell

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**FIGURE 1.** Characterization of human A172 and U87-MG glioblastoma cell lines. A, GM-CSF ELISA of supernatants collected from tumor cell lines (5 × 10^5 cells/ml) plated 24 h and treated with buffer control or 10 ng/ml TNF-α for an additional 24 h. The mean concentration ± SEM is displayed. n = 3, *p < 0.0001 versus control. B, Flow cytometry analysis of VCAM-1 and ICAM-1 geometric mean fluorescence intensity (GMFI) from tumor cell lines (5 × 10^5 cells/ml) plated 24 h and treated with buffer control or 10 ng/ml TNF-α for an additional 24 h ± SEM. n = 3. *p < 0.0001 versus control, †p < 0.0001 versus control, ‡p < 0.0001 versus control, p < 0.0001 versus control. C, A representative immunoblot and ImageJ assessment of GBM RAGE compared with positive (DU-145 prostate carcinoma) and negative (H358 NSCLC) controls. Data charted represent RAGE mean densitometry relative to actin ± SEM, n = 5. *p < 0.0006 versus H358, †p = 0.0007 versus DU-145, ‡p = 0.002 versus A172.
lines was not significantly different from the media control. These data indicate that eosinophils do not preferentially adhere in response to coculture with the U87-MG cells compared with the A172 cells in a 30-min time frame. Pretreatment of the cell lines with TNF-α for 24 h enhanced eosinophil adhesion to the plate and to the A172 cells, but not to the U87-MG cells. Preincubation (1 h) with GM-CSF neutralizing Abs reduced adhesion, most significantly for the GM-CSF control and for the A172 cells stimulated with TNF-α. These results indicate that eosinophils are more adhesive in the presence of the TNF-α–treated A172 cells, which produce lower levels of the cytokine GM-CSF compared with U87-MG cells (Fig. 1A).

**Immunofluorescence of eosinophil adherence in cocultures**

To further assess the adhesive functions of eosinophils in cocultures with glioblastoma cell lines, we performed immunofluorescence assays. Similar to the results of the EPO assay, the TNF-α–treated A172 cell line appeared to induce eosinophil adherence after 10-min culture and immunofluorescent microscopy examination (Fig. 2B). Addition of GM-CSF neutralizing Abs (clone BVD2-23B6) to TNF-α–treated A172 cell line cultures 1 h before the addition of eosinophils mitigated the adhesive response (Fig. 2B). Significant eosinophil adherence was not identified in control A172 cell line control.

**FIGURE 2.** Human blood eosinophil adherence as measured by EPO activity and immunofluorescence. A, Media controls (buffer, 100 pg/ml GM-CSF, 10 ng/ml TNF-α) or tumor cell lines stimulated (24 h) with buffer control or 10 ng/ml TNF-α were treated with an isotype control or GM-CSF neutralizing Ab (1 h) before adding eosinophils. An EPO assay was performed after 30-min incubation with eosinophils as described in Materials and Methods. Data represent the average relative number ± SEM of eosinophils adhered. n = 5. *p ≤ 0.0001 versus respective isotype control, †p ≤ 0.009 versus media control, ‡p ≤ 0.005 versus TNF media control, §p < 0.0001 versus A172 cell line control. B, Media controls (buffer, 100 pg/ml GM-CSF, 10 ng/ml TNF-α) or tumor cell line cultures stimulated (24 h) with buffer control or 10 ng/ml TNF-α were treated with an isotype control or GM-CSF neutralizing Ab (1 h) before adding eosinophils. After 10-min incubation with eosinophils, the cells were washed, fixed, and stained as described in Materials and Methods. Data represent the average number ± SEM of eosinophils adhered. n = 4. *p ≤ 0.0001 versus respective isotype control, †p ≤ 0.006 versus media control, ‡p ≤ 0.004 versus TNF media control, §p < 0.0001 versus A172 cell line control.

**FIGURE 3.** Human blood eosinophil viability in response to coculture with A172 and U87-MG spheroids. Human blood eosinophils (2 × 10^5/ml) were cultured above 0.5% w/v agarose, 48-well plate, ±100 pg/ml GM-CSF or glioblastoma cells (5 × 10^4/ml) for 4 d. A, Cells were positively selected for CD11b expression and negatively selected for propidium iodide stain. The percentage average viability ± SEM is displayed. n = 4. **p < 0.0001 versus media control.** B, Cells cultures were resuspended in 50 μl media and diluted 1:2 in trypan blue. Cells were identified as viable via trypan blue exclusion. The percentage average viability ± SEM is displayed. n = 3. **p < 0.0001 versus media control.** C, Supernatants from 4-d cultures were assessed for the presence of GM-CSF via ELISA (as detailed in Materials and Methods). The mean concentration ± SEM is displayed. n = 3. **p < 0.0001 versus all other samples.**
cultures (Fig. 2B) or U87-MG cultures generated in the presence or absence of TNF-α (data not shown).

Eosinophil viability in response to glioblastoma spheroid coculture

Tumor cell lines suspended above agar are known to form spheroids, involving a diverse population of quiescent, hypoxic, and necrotic cells similar to human tumors and equally resistant to radiation and experimental drugs (36, 37). Spheroids in culture with immune cells have previously been used to model the tumor microenvironment and examine potential immunotherapeutic treatments (38). A previous study has also identified enhanced eosinophil viability in cocultures of human biologically active GBM explants and autologous peripheral blood leukocytes (39). To examine whether growing tumor spheroids affect eosinophil viability, we cocultured eosinophils with GBM spheroids for 4 d. Tumor cell lines were evaluated for CD11b expression via flow cytometry analysis and determined to be negative for this cell adhesion molecule (data not shown). The expression of CD11b has been previously characterized on eosinophils (40) and was therefore used as a positive selection marker in identifying eosinophils in cocultures. As a positive indicator of viability, GM-CSF was added to eosinophil monocultures similar to our previous study (41). Viability was determined by the absence of propidium iodide stain, revealing increased eosinophil viability from four different patients in the presence of GM-CSF or GBM spheroids (Fig. 3A). These data were confirmed with three additional patients via analysis of live cells using a trypan blue exclusion assay (Fig. 3B). Concomitant examination of 4-d culture supernatants by ELISA revealed the presence of GM-CSF. Notably, as shown in Fig. 3C, we observed that the diminished levels of GM-CSF found in the positive control could still maintain eosinophil viability. Significant production of GM-CSF in U87-MG cell cultures did not further alter eosinophil viability compared with

![Figure 4](http://www.jimmunol.org/)

**FIGURE 4.** Human blood eosinophil viability in response to GBM cell line-conditioned media. Human blood eosinophils (2 \( \times \) 10^5/ml) were cultured above 0.5% w/v agarose, 48-well plate, \( \pm 100 \) pg/ml GM-CSF or GBM cell line-conditioned media for 4 d. Cells were gated (as shown in Supplemental Fig. 2) and negatively selected for propidium iodide stain. A, The percentage average viability in response to media controls or conditioned media is displayed. \( n = 5 \), \( \ast p \leq 0.001 \) versus media control. B, The percentage average viability in response to coculture with anti–GM-CSF (clone BV2D-23B6) or isotype control Abs was added. Cultures were maintained for 3 h. Cells were gated (as shown in Supplemental Fig. 4), negatively selected for propidium iodide stain, and positively selected for CD69 expression. A, The percentage average CD69 expression \( \pm \) SEM in response to media controls or conditioned media is displayed. \( n = 5 \), \( \ast p < 0.0001 \) versus media, \( \dagger p < 0.0001 \) versus TNF-α, \( \ddagger p < 0.0001 \) versus A172, \( \times p < 0.0001 \) versus U87-MG. B, The percentage average CD69 expression \( \pm \) SEM in response to coculture with anti–GM-CSF (clone BV2D-23B6) or isotype control Abs is displayed. \( n = 4 \), \( \ast p \leq 0.0001 \) versus media control. C, The percentage average viability in response to GM-CSF cytokine depletion (clone BV2D-23B6) or isotype controls is displayed. \( n = 3 \), \( \ast p \leq 0.0001 \) versus media control.
the positive control or the observations associated with the A172 cell cultures. These results suggest that the very low levels of GM-CSF in the A172 cell cultures are sufficient for maximum viability and/or that another factor(s) may contribute to eosinophil viability in the A172 cell cultures.

**Eosinophil viability in response to GBM cell line-conditioned media**

Soluble factors derived from tumor cells have been found to affect the activation of human monocytic cells (31). To test the idea that soluble factors produced by tumor cells induced eosinophil survival as suggested by the data in Fig. 3, eosinophils were cultured in GBM cell line-conditioned media for 4 d and analyzed by flow cytometry. As shown in Fig. 4A, GBM cell line-conditioned media are also able to induce the survival of eosinophils from five different patients, similar to the GM-CSF positive control, comparable with spheroid coculture (Fig. 3A,3B), and despite differential production levels of GM-CSF between tumor cell lines (Fig. 3C).

**Effect of GM-CSF neutralization on GBM cell line-conditioned media-induced eosinophil viability**

To assess whether the soluble factor involved in GBM cell line-conditioned media-induced viability is GM-CSF, we added neutralizing Abs from two separate vendors to 4-d cultures. As shown in Fig. 4B, GBM cell line-conditioned media-induced eosinophil viability from four different patients is reduced in the presence of GM-CSF neutralizing (clone BVD2-23B6) Abs but not in the presence of the isotype controls. Additional viability analyses of human blood eosinophils from three different patients after GM-CSF neutralization using an Ab from an alternative source (clone 3209) confirmed these results (Supplemental Fig. 3). These combined data suggest that low levels of GM-CSF, produced by tumor cell lines or eosinophils in response to the conditioned media, are able to enhance eosinophil survival.

**Effect of GM-CSF depletion on GBM cell line-conditioned media-induced eosinophil viability**

Because eosinophils have been suggested to produce GM-CSF in response to various stimuli (42, 43), GM-CSF cytokine depletion of tumor cell-conditioned media was performed before culturing eosinophils. As shown in Fig. 4C, GBM cell line-conditioned media-induced eosinophil viability from four different patients is reduced after GM-CSF cytokine depletion but not in response to the isotype controls. These data suggest that GM-CSF-mediated viability responses are a function of tumor-derived GM-CSF.

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**FIGURE 6.** Human blood eosinophil CD11b expression in response to GBM cell line-conditioned media. Human blood eosinophils (2 × 10^6/ml) were cultured above 0.5% w/v agarose, 48-well plate, ±100 pg/ml GM-CSF, 10 ng/ml TNF-α, or GBM cell line-conditioned media generated in the presence or absence of 10 ng/ml TNF-α. Cultures were maintained for 24 h. A, Cells were negatively selected for propidium iodide stain and positively selected for CD11b expression. B, The percentage average CD11b expression ± SEM in response to media controls or conditioned media is displayed. n = 3. *p < 0.01 versus control, †p < 0.03 versus TNF-α.
Eosinophil CD69 expression in response to GBM cell line-conditioned media

A strong inducer of eosinophil activation is GM-CSF, as exhibited by CD69 expression (44). To examine whether GBM cell line-conditioned media also induce CD69 expression, we cultured eosinophils with GBM cell line-conditioned media for 3 h before analysis via flow cytometry. Because previous research has indicated that TNF-α induces GM-CSF production by GBM cells (45), 10 ng/ml TNF-α was added to selected GBM cultures 24 h before harvesting the GBM cell line-conditioned media. As shown in Fig. 5, significant eosinophil CD69 expression from six different patients occurred in response to U87-MG, but not A172 cell-conditioned media, compared with media alone and the GM-CSF media control. Addition of TNF-α during the generation of GBM cell line-conditioned media induced CD69 expression in A172 cultures and enhanced the expression in U87-MG cultures compared with TNF-α and respective GBM cell line-conditioned media alone. The absence of CD69 expression in the presence of A172 cell-conditioned media may be a response to the lower basal levels of GM-CSF produced by these cells compared with the U87-MG (Fig. 1A).

Effect of GM-CSF neutralization on GBM cell line-conditioned media-induced eosinophil CD69 expression

To determine whether tumor-derived GM-CSF induces eosinophil CD69 expression, neutralizing Abs to GM-CSF were added to eosinophils cultured in GBM cell line-conditioned media and compared with a GM-CSF positive control. As shown in Fig. 5B, eosinophil CD69 expression from four different patients is reduced in the presence of GM-CSF neutralizing Abs with significant reductions found in TNF-α–generated conditioned media, the U87-MG-conditioned media alone, and the GM-CSF control.

Effect of GM-CSF depletion on GBM cell line-conditioned media-induced eosinophil CD69 expression

Because eosinophils have been indicated to produce GM-CSF in response to various stimuli (42, 43), GM-CSF cytokine depletion of tumor cell-conditioned media was performed before culturing eosinophils. As shown in Fig. 5C, GBM cell line-conditioned media-induced eosinophil CD69 expression from three different patients is reduced after GM-CSF cytokine depletion, but not in response to the isotype controls, similar to Fig. 5B. These data suggest that GM-CSF–induced CD69 expression is a function of tumor cell–derived GM-CSF and not eosinophil autocrine activity.

GBM cell line-conditioned media-induced eosinophil CD11b expression

The eosinophil adhesion molecule CD11b is known to be responsive to GM-CSF (27). To test whether GBM cell line-conditioned media affects eosinophil CD11b expression, we cultured eosinophils with GBM cell line-conditioned media for 24 h before analysis via flow cytometry. As shown in Fig. 6, significant eosinophil CD11b expression from three different patients occurred in response to U87-MG but not A172 cell-conditioned media. Addition of TNF-α during the generation of GBM cell line-conditioned media induced significant CD11b expression in A172 cell cultures and maintained U87-MG CD11b expression compared with media alone, GM-CSF, and TNF-α treatments.

GBM cell line-conditioned media-induced eosinophil S100A9 release

Induction of CD11b is reportedly dependent on the presence of a cytoplasmic calcium-binding protein, S100A9 (46). Release of S100A9 in the tumor microenvironment may be tumorostatic or tumorigenic depending on the concentration of S100A9 and tumor type (47, 48). To examine whether eosinophils produce S100A9, we cultured eosinophils with GBM cell line-conditioned media for 24 h, and the cell-free conditioned media were examined for S100A9 expression via immunoblot. As shown in Fig. 7, S100A9 was identified in cocultures involving media controls and GBM cell line-conditioned media generated in the presence or absence of TNF-α from three different patients.

Effect of dexamethasone on GM-CSF production by tumor cell lines

Eosinophil recruitment to the lung is reduced by dexamethasone (49), a common corticosteroid administered to GBM patients with peritumoral edema (50). Dexamethasone is also indicated to inhibit the release of GM-CSF from human primary T cells (51), suggesting that similar responses may occur in tumor cell lines known to produce GM-CSF. To test whether dexamethasone affects GBM cell line GM-CSF production, we plated 5 × 10⁵ cells/ml for 24 h before the addition of vehicle control, 10 ng/ml TNF-α, and increasing concentrations of dexamethasone, followed by an additional 24-h incubation. As shown in Fig. 8, TNF-α–induced, but not basal, GM-CSF production by the GBM tumor cell lines is significantly reduced by dexamethasone. Tumor cell line viability was not inhibited by dexamethasone or TNF-α treatments (Supplemental Fig. 5).

Tumor cell line growth in response to eosinophil-conditioned media

Eosinophil-conditioned media generated in the presence or absence of GM-CSF has been shown to enhance endothelial cell proliferation (52). To assess whether soluble factors produced by eosinophils affect glioblastoma cell growth, we cultured cell lines with eosinophil-conditioned media and subjected them to an MTS assay. As shown in Fig. 9, soluble factors from eosinophils significantly induced glioblastoma cell growth compared with controls. These conditions resulted in 1.7- and 1.3-fold increases in respective A172 and U87-MG viability over the media control. Generation of eosinophil-conditioned media in the presence of 100 pg/ml GM-CSF enhanced the effect with 2.1- (A172) and 1.6-fold (U87-MG) increases in viability over the GM-CSF media control.

Discussion

The reported inverse correlation between atopic disease and glioblastoma risk (12–15) suggests that an immune cell pivotal to...
the allergic response, such as the eosinophil (6), may also function in an anticancer response. Because cytokines such as GM-CSF and adhesion molecules (CD11b/CD18, CD49d/CD29) function in the recruitment of eosinophils in atopic disease (27), similar mechanisms may be essential to the migration of eosinophils into tumor tissue. Examination of glioblastoma cell lines indicated that the U87-MG but not the A172 cell line expressed significant basal levels of GM-CSF and ICAM-1, and higher levels of RAGE (Fig. 1) and extracellular matrix proteins (54), or additional cytokines (IL-1β, TGF-β) produced by U87-MG but not A172 cells (55).

Coexpression of GM-CSF and its receptor have been found exclusively in cultures derived from grade IV astrocytomas (GBM), but not in lower grades or normal brain tissue (56). Because dexamethasone is a potent inhibitor of GM-CSF (51) and a common corticosteroid administered to GBM patients with peritumoral edema (50), examination of tumor cell line GM-CSF production in the presence of dexamethasone was assessed. In Fig. 8, TNF-α–induced but not basal GM-CSF production was significantly inhibited by dexamethasone. In Supplemental Fig. 5, tumor cell proliferation was not reduced but rather enhanced by dexamethasone, similar to previous assessments of glioma cell lines (57) and at concentrations within the physiological range of the corticosteroid administered to GBM patients with peritumoral edema (50).

Because treatment of GBM cell lines with TNF-α led to increased tumor cell-derived GM-CSF production (Figs. 1A, 8), additional studies were performed to assess possible differential TNF-α–induced responses. Stimulating A172 cells with TNF-α and inclusion of TNF-α in the generation of A172-conditioned media significantly enhanced respective eosinophil adhesion (Fig. 2A, 2B) and CD69 expression (Fig. 5) that was mitigated by the addition of GM-CSF neutralizing Abs (Figs. 2A, 2B, 5B) or GM-CSF cytokine depletion (Fig. 5C). Similar treatment of U87-MG cells with TNF-α did not yield enhanced adhesion (Fig. 2) but did enhance CD69 expression (Fig. 5) in a GM-CSF–dependent manner. In the absence of TNF-α, only the U87-MG cell line induced CD69 activation that was also reduced by the addition of GM-CSF neutralizing Abs (Fig. 5). Interestingly, eosinophils were found to colocalize with either A172 or U87-MG spheroids with enhanced eosinophil clustering and recruitment noted in response to increased incubation and/or TNF-α treatment (Supplemental Fig. 1). These differential functions may be in response to the levels of GM-CSF produced by tumor cells (Figs. 1A, 8), production of the adhesion-associated molecule S100A9 by eosinophils (C.S. Curran and P.J. Bertics, submitted for publication) (53) (Fig. 7), changes in eosinophil CD11b expression (Fig. 6), culture conditions (Fig. 2, Supplemental Fig. 1), differential expression of tumor cell adhesion ligands (Fig. 1B) and extracellular matrix proteins (54), or additional cytokines (IL-1β, TGF-β) produced by U87-MG but not A172 cells (55).

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previously assessed human brain tissue biopsy specimens (58). Dexamethasone has also been reported to reduce eosinophil recruitment (49), induce eosinophil apoptosis (59), and inhibit eosinophil TNF-α–induced GM-CSF production (42). Focal expression of TNF-α has been identified in infiltrating leukocytes in GBM tumors (60). Dexamethasone therapy (16 mg/day) in some GBM cases reduced the imaging of lesions on contrast-enhanced scans (61, 62), possibly by inhibiting immune cell recruitment via reduced capillary permeability at the brain–tumor barrier (63), inducing eosinophil apoptosis (59), and/or reducing localized GM-CSF production (Fig. 8) (42). Thus, the efficacy of dexamethasone treatment may be a factor of the tumor microenvironment and whether the established immune response is tumorigenic or immunogenic.

In examining the eosinophil immune response, GBM cell lines were cultured with eosinophil-conditioned media and assessed for proliferation via MTS assay. As shown in Fig. 9, eosinophil-conditioned media, generated in the presence or absence of GM-CSF, enhanced glioblastoma cell growth compared with respective controls. These data are supported by examining A172 CFSE expression. Eosinophils stimulated with GM-CSF are known to produce amphiregulin and TGF-α, ligands highly implicated in tumor promotion via a common receptor, epidermal growth factor receptor (EGFR) (64–66). In primary GBM, amplification of the EGFR gene and subsequent overexpression of EGFR protein is the most common genetic alteration (67). Release of S100A9 (Fig. 7) was increased in GBM and other GM-CSF production (Fig. 8) (42). Thus, the efficacy of dexamethasone treatment of GBM may be a factor of the tumor microenvironment and whether the established immune response is tumorigenic or immunogenic.

In summary, we have shown that eosinophils are more viable and activated in the presence of GBM tumor cell lines or GBM cell line-conditioned media. These eosinophil responses are, in part, regulated by tumor cell-derived GM-CSF as indicated by neutralization and cytokine depletion experiments. Eosinophils, in the presence or absence of GM-CSF, produced growth factors essential to tumor cell viability, indicating a potential cooperative function of eosinophils in tumor promotion/progression. Thus, the inverse correlations reported between atopic disease and GBM risk cannot be attributed to the functional responses of eosinophils alone. The enhanced GBM production of GM-CSF and expression of adhesion ligands (ICAM-1, VCAM-1) in the presence of TNF-α suggest a synergy with microglial cells in the recruitment and activation of eosinophils. These findings offer insight into GBM and other GM-CSF secreting tumors [colon (71), prostate (72), and skin (73)] known to recruit eosinophils (5, 24, 74), and emphasize the need to understand the immunological networks within the tumor microenvironment in developing more effective immunotherapeutic protocols.

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