Interferon-β Induces Loss of Spherogenicity and Overcomes Therapy Resistance of Glioblastoma Stem Cells

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Abstract
Glioblastoma is the most common malignant brain tumor in adults and characterized by a poor prognosis. Glioma cells expressing O6-methylguanine DNA methyltransferase (MGMT) exhibit a higher level of resistance toward alkylating agents, including the standard of care chemotherapeutic agent temozolomide. Here, we demonstrate that long-term glioma cell lines (LTL) as well as glioma-initiating cell lines (GIC) express receptors for the immune modulatory cytokine IFN-β and respond to IFN-β with induction of STAT-3 phosphorylation. Exposure to IFN-β induces a minor loss of viability, but strongly interferes with sphere formation in GIC cultures. Furthermore, IFN-β sensitizes LTL and GIC to temozolomide and irradiation. RNA interference confirmed that both IFN-β receptors, R1 and R2, are required for IFN-β-mediated sensitization, but that sensitization is independent of MGMT or TP53. Most GIC lines are highly temozolomide-resistant, mediated by MGMT expression, but nevertheless susceptible to IFN-β sensitization. Gene expression profiling following IFN-β treatment revealed strong upregulation of IFN-β-associated genes, including a proapoptotic gene cluster, but did not alter stemness-associated expression signatures. Caspase activity and inhibition studies revealed the proapoptotic genes to mediate glioma cell sensitization to exogenous death ligands by IFN-β, but not to temozolomide or irradiation, indicating distinct pathways of death sensitization mediated by IFN-β. Thus, IFN-β is a potential adjunct to glioblastoma treatment that may target the GIC population. IFN-β operates independently of MGMT-mediated resistance, classical apoptosis-regulatory networks, and stemness-associated gene clusters. Mol Cancer Ther; 13(4); 948–61. ©2014 AACR.

Introduction
Glioblastomas are characterized by infiltrative growth and resistance to cell death induction. Despite multimodal therapy, tumor progression occurs inevitably and survival remains in the range of months (1–3). Early therapy failure is associated with the expression of O6-methylguanine-DNA-methyltransferase (MGMT), a DNA repair protein that accounts for glioma cell resistance by counteracting the effects of alkylating chemotherapy (4). MGMT has become an important molecular marker and is now implemented in clinical diagnostics as predictive biomarker for benefit from alkylating chemotherapy and clinical outcome (5–7). Patients with a nonmethylated MGMT promoter are prone to therapy failure with standard alkylating chemotherapy, and to date, effective approaches for this large group of patients, comprising more than half of all the patients with glioblastoma, are still lacking, including dose intensification of temozolomide (8).

Recently, a subfraction of glioma cells exhibiting stem cell-like properties (stem-like glioma cells), referred to as glioma-initiating cells (GIC), has been identified (9, 10). GICs are thought to have the ability of self-renewal, tumor initiation, and pluripotency and have been proposed to account for the ultimately lethal nature of glioblastoma. They may contribute to therapy resistance in vivo and therefore promote tumor progression. The value of GIC cultures and their MGMT status as a model to study resistance to temozolomide in glioblastoma has remained controversial. Among a panel of 20 GIC lines, some were sensitive to temozolomide, which was associated with low MGMT protein levels, but not MGMT promoter methylation, and the MGMT promoter status was thus not strongly predictive of response to temozolomide (11). High temozolomide sensitivity of GIC cultures lacking MGMT expression has been described in vitro (12). Finally, the frequency of MGMT promoter-methylated alleles in glioblastomas may range from 10% to 90%, but...
methylated alleles were enriched in GIC cultures (13). Considering the limited activity of current standards of care, new approaches should take into account this novel target cell population.

IFN-β, a member of the IFN class I family, exerts numerous functions for cellular differentiation, cell growth, and immune responses. IFN-β signaling is mediated through binding to a type II cytokine receptor, involving heterodimerization of 2 IFN-α/β receptor subunits, IFNAR-1 and IFNAR-2. Downstream signaling pathways involve the Janus kinase/signal Transducers and Activators of Transcription (JAK/STAT) pathway (14) and lead to accumulation of myxovirus resistance 1 (Mxα) protein, a GTPase interfering with the cytoskeletal structure (15, 16). MxA induction is an established marker for responsiveness to IFN-β (17, 18).

IFN-β has gained great clinical impact in the treatment of multiple sclerosis. Its safety profile in patients with brain disease has therefore been firmly established. Moreover, IFN-α/β were the first agents to show a significant survival benefit in randomized trials in malignant melanoma (19). The mechanisms mediating antitumor effects of IFN may involve direct cytostatic, antiangiogenic, or immunomodulatory activities. IFN-β has been reported to sensitize human glioma cell lines to temozolomide in a TP53- and MGMT-dependent manner (20, 21). These reports, however, were based on findings in T98G and U251MG, both being TP53-mutant cell lines (22, 23). Moreover, IFN-β has been attributed anti–stem cell properties in glioma models (24). Finally, clinical trials exploring the addition of IFN-β to radiotherapy plus temozolomide have been initiated and interpreted as promising (25, 26). These data prompted us to evaluate the potential role of IFN-β as a component of future, innovative treatment approaches for glioblastoma in more detail. In brief, we demonstrate profound anti-GIC activity of IFN-β as well as IFN-β–mediated sensitization to temozolomide and irradiation, but exclude MGMT and TP53 as primary mediators of these effects. IFN-β exposure induces characteristic IFN-β-associated gene clusters, but does not alter the stemness signature of GIC. A proapoptotic gene signature induced by IFN-β is functionally relevant, but mediates neither anti-GIC properties nor sensitivity to temozolomide or radiotherapy.

Materials and Methods

Materials and cell lines

The human U87MG and T98G glioma cell lines, K562 leukemia cells, and MCF-7 breast adenocarcinoma cells were purchased from the American Type Culture Collection. The other long-term cell lines (LTL) were kindly provided by N. de Tribolet (Department of Neurosurgery, University Hospital, Lausanne, Switzerland). LNT-229 cells cultured in our laboratory express TP53 wild-type transcriptional activity (23). The generation of LNT-229 cells depleted of TP53 or overexpressing MGMT has been described (23, 27). MGMT-silenced LN-18 cells were generated by transfection with pSUPER puro encoding MGMT short hairpin (sh) RNA using Metafectene Pro transfection reagent (Biontex Laboratories GmbH; ref. 28). The GIC cell lines GS-2, GS-5, GS-7, GS-8, and GS-9 have been characterized elsewhere (29). LTL were cultured in Dulbecco’s modified Eagle medium containing 10% fetal calf serum (FCS), 2 mmol/L glucose and penicillin (100 IU/mL)/streptomycin (100 μg/mL). GS culture spheres were maintained in neurobasal medium supplemented with 2% B-2 supplement, 1% GlutaMAX, 20 ng/mL EGF, 20 ng/mL fibroblast growth factor, and 32 IE/mL heparin. K-562 cells were maintained in RPMI-1640 supplemented with 1 mmol/L sodium pyruvate (Gibco Life Technologies) and 10% FCS. Temozolomide was provided by Schering-Plough (Kenilworth). A stock solution of temozolomide at 200 mmol/L was prepared in dimethyl sulfoxide. Recombinant IFN-β1b was purchased from AbD Serotec, reconstituted to a concentration of 1,000,000 IU/mL with distilled water. The following antibodies were used: STAT-3 and phospho-STAT-3, caspase-3, and LC3A/B from Cell Signaling Technology; glyceraldehyde 3-phosphate dehydrogenase (GAPDH) from Everest Bio-tech; TNF-related apoptosis inducing ligand (TRAIL) and XIAP–associated factor 1 (XAF-1) from Santa Cruz tech; TNF-related apoptosis inducing ligand (TRAIL) and XIAP–associated factor 1 (XAF-1) from Santa Cruz Biotechnology; caspase-8 from Enzo Life Science; Glial fibrillary acidic protein (GFAP) from Dako; Nestin from Zytomed Systems GmbH; β-III tubulin from Abcam. Mega-Fas–ligand (MFL) was provided by Topotarget. The MxA antibody was kindly provided by O. Haller and G. Kochs (Department of Virology, University of Freiburg, Germany). All other reagents, including anti-β2, 3′-cyclic nucleotide 3′-phosphodiesterase (CNPase) antibody, O6-benzylguanine (O6-BG), and salinomycin, were purchased from Sigma. For irradiation experiments, cells were irradiated in a Co-radiation source (Gebruder Sulzer, Thermische Energiesysteme, 60-Co) at 1, 3, and 5 Gy at 24 hours after IFN-β exposure.

Polymerase chain reaction

Total RNA was prepared using the NucleoSpin System (Macherey-Nagel AG) and transcribed using random primers (Bioconcept/NEB, Bioconcept) and Superscript II reverse transcriptase (Invitrogen). For reverse transcriptase PCR, the conditions were: 35 cycles, 94°C/45 seconds, specific annealing temperature (54°C for IFNAR-1, 52°C for IFNAR-2, 51°C for GAPDH)/45 seconds, 72°C/1 minute. For real-time (quantitative) qPCR, cDNA amplification was monitored using SYBRGreen chemistry on the 7300 Real time PCR System (Applied Biosystems). The conditions were as follows: 40 cycles, 95°C/15 seconds, 60°C/1 minute. Data analysis was done using the ΔΔCt method for relative quantification. The following specific primers were used: GAPDH forward: 5′-CTTCTGCT-CCTCCGTGGCAGC-3′, GAPDH reverse: 5′-TGACG-GATGTGCCGCTGCT-3′; IFNAR-1 forward: 5′-AATGCTGCGAACGTCTTTATGC-3′, IFNAR-1 reverse: 5′-TGCTTGCCCTTTCGTC-3′; IFNAR-2 forward: 5′-TCTGACATCCATCCTGCTGAGC-3′, IFNAR-2 reverse: 5′-TCTGACATCCATCCTGCTGAGC-3′; GAPDH forward: 5′-CTTCTGCT-
reverse: 5'-CAG GGA TGC ACG CTT GTA ATC-3'; XAF1 forward: 5'-AGC AGG TTG GGT GTA CGA TG-3'; XAF1 reverse: 5'-TGA GCT GCA TGT CCA GTT TG-3'; TRAIL forward: 5'-TGC GAG CTG ATC GTG ATC TTC-3'; TRAIL reverse: 5'-GCT GGT TGG TAA AGT ACA CG TA-3'.

**Flow cytometry, cell cycle, and viability assays**

Differentiated glioma cells and sphere cultures were detached respectively dissociated using Accutase (PAA Laboratories) and blocked with 2% FCS in PBS. The cells were incubated for 30 minutes on ice using the following PE-labeled antibodies: anti–IFNAR-1 or anti–IFNAR-2 antibodies (PBL interferon source) for IFNAR experiments and anti-CD133/2-PE (Miltenyi Biotec) for stem cell marker experiments. Flow cytometry was performed with a CyAn flow cytometer (Beckman Coulter). Signal intensity was calculated as the ratio of the mean fluorescence of the specific antibody and the isotype control antibody (specific fluorescence index). Dead cells were gated out. For some analyses, cells were permeabilized by Fix/Perm Buffer Set (Lucerna Chem AG, Biolegend). For analysis of cell death, cells were grown in 6-well plates, incubated with IFN-β at 150 IU/mL for 24 hours, washed in PBS, and allowed to grow for 48 hours. Annexin V fluorescence detection was performed in annexin V-PE and PI apoptosis detection kit (CalZyme). The primary antibody overnight at 4°C and 1 hour at room temperature for secondary antibodies. Staining was performed as suggested by the manufacturer, using IFNAR-1 antibody from antibodies-online.com and IFNAR-2 antibody from Abcam. The cells were treated as indicated and lysed in lysis buffer containing 50 mmol/L Tris-HCl, 120 mmol/L NaCl, 5 mmol/L EDTA and 0.5% NP-40. Protein (20 μg/lane) was separated on 10% acrylamide gels. After transfer to nitrocellulose (Bio-Rad), the blots were blocked in Tris-buffered saline containing 5% skim milk and 0.05% Tween 20 and incubated overnight at 4°C with primary antibodies and 1 hour at room temperature for secondary antibodies. Visualization of protein bands was accomplished using horseradish peroxidase-coupled secondary antibodies (Santa Cruz Healthcare) and enhanced chemiluminescence (Pierce/Thermo Fisher).

**Immunocytochemistry and immunofluorescence microscopy**

For stemness experiments, the cells were exposed to IFN-β (150 IU/mL) for 48 hours and cytospin samples were prepared, fixed in 4% PFA, and blocked in either blocking solution (Candor Bioscience GmbH) for GFAP, β-III tubulin or CNPase, or PBS containing 10% swine serum and 0.3% Triton X for nestin, and exposed to the primary antibody overnight at 4°C and 30 minutes at room temperature for secondary antibodies. Detection was performed with DAB detection system (Dako) for 5 minutes at room temperature, and slides were mounted in Eukitt (Sigma-Aldrich). Counterstaining was performed with hemalum. For IFNAR receptor staining, cytospin samples of LTL or GIC were processed for further treatment. Staining was performed as suggested by the manufacturer, using IFNAR-1 antibody from antibodies-online.com and IFNAR-2 antibody from Abcam.

**RNA interference-mediated gene silencing**

For transient transfections, 2.5 × 10^6 glioma cells were seeded in a 6-well plate and transfected with 100 mmol/L of specific or scrambled control small interfering (si) RNA, using Metafectene Transfection reagent (Biontex). siRNA was purchased from Dharmacon/Thermo Fisher using siGENOME SMARTpool targeting human IFNAR-1 and human IFNAR-2. Samples were collected 48 hours after transfection and processed for further treatment.

**Reporter assay**

Dual luciferase/renilla assays were carried out with cotransfection of 150 ng of the specific reporter construct and 20 ng of the renilla reniformis-CMV (pRL-CMV) control plasmid (Promega). Luciferase activity was normalized to constitutive renilla activity. The pGL2-Luc MGMT construct (30) was a kind gift from Dr. S. Mitra (Sealy Center for Molecular Science and Department of Human Biological Chemistry and Genetics, University of Texas Medical Branch, Galveston, TX). The TP53-Luc construct has been described elsewhere (31).
Caspase activity assay
Cells were seeded at a density of 1,000 cells per well in a 6-well plate and treated as described above with either IFN-β and temozolomide alone or in combination with or without ZVD-fmk, with either MFL (Mega-FAS-ligand) or staurosporine (STS) as positive control. Cells were incubated in lysis buffer (25 mmol/L Tris/HCL, 60 mmol/L NaCl, 2.5 mmol/L EDTA, 0.25% NP40) for 10 minutes, and the substrate Ac-DEVD-amc was added at a concentration of 20 μmol/L. Fluorescence was assessed at 360 nm wavelength every 15 minutes until extinction of fluorescence (32).

Microarray-based gene expression profiling
Technical details are provided in the Supplementary Methods. Array records are deposited under GEO accession number GSE53213.

Statistical analysis
Data are representative of experiments performed three times with similar results. Where indicated, analysis of significance was performed using the two-tailed Student t test. Synergy of irradiation or temozolomide and IFN-β was assessed by the fractional product method (33) where indicated and differences of 10% of observed versus predicted (additive) effect were considered synergistic. For the analysis of functional gene interactions, the Search Tool for the Retrieval of Interacting Genes/Proteins (STRING) Version 9.05 at http://string-db.org (34) was used. Highest confidence settings were applied, integrating combined scores higher than 0.900. Cluster analysis was performed by application of the Markov Cluster algorithm (MCL). Disconnected nodes were hidden from the image.

Results
IFNAR are expressed in human glioma cells
In total, 12 LTL and 5 GIC were assessed for mRNA expression of IFNAR-1 and -2 by RT-PCR. All lines expressed transcripts for both receptor subunits (Fig. 1A). IFNAR-1, in contrast to IFNAR-2, was not detected at the surface on any glioma cell line by flow cytometry (Fig. 1B, left), but was detected by immunostaining (Fig. 1B, right). Permeabilization of the cells or scraping of cells instead of using accutase did not produce a specific signal for IFNAR-1 on flow cytometry either. Specific fluorescence intensity (SFI) values for IFNAR-2 above 3 were never seen in GIC, but in all LTL (data not shown).

IFN-β signaling in glioma cells involves Mxα and STAT-3
To ensure that IFN-β induces classical signaling pathways in glioma cells, we investigated whether STAT-3, the proposed signal transducer in response to IFN-β in gliomas, and the IFN-α/β-regulated protein Mxα, a classical marker for cellular responsiveness to IFN-β, were induced. Immunoblot confirmed that STAT-3 phosphorylation levels increased shortly after exposure to IFN-β, with a peak at 30–60 minutes, with no relevant concentration dependency between 50 and 500 IU/mL, in LTL and GIC (Fig. 1C). Likewise, the exposure to IFN-β led to a concentration-dependent increase of MxA protein in LNT-229 (Fig. 1D, top row) or LN-18 cells (data not shown), in a time-dependent manner (Fig. 1D, bottom row), with first marked elevation of protein levels at a concentration of 150 IU/mL at 24 hours.

IFN-β induces cell-cycle arrest in glioma cells and causes sphere disruption in GIC
Within the concentration and time ranges of our experiments, IFN-β induced a reduction of G1 cells in all cell lines, associated with increases in S cells or G2–M cells or both. Moreover, there was an increase in sub-G1 cells, indicating minor cell death induction (Fig. 2A). A moderate induction of necrotic rather than apoptotic cell death was confirmed by Annexin V/PI flow cytometry, defined by an increase of the PI-positive fraction (Fig. 2B). Cellular staining and immunoblot for autophagy were negative in response to IFN-β (Fig. 2C and D).

We also assessed a possible modulation of spherogenicity of GIC by IFN-β. When exposed to 150 IU/mL IFN-β, singularized GIC cultures showed a reduced sphere formation at 1,000–10,000 cells per well; lower cell numbers did not result in efficient sphere formation, independent of IFN-β exposure (Fig. 2B). Conversely, exposure of fully formed spheres to 150 IU/mL IFN-β led to sphere disaggregation, with lesser and significantly smaller spheres remaining after 2 weeks of culture, as assessed by sphere count and absorbance (Fig. 2F). The single cells detaching from the sphere were viable during the first days after sphere disaggregation, but underwent cell death after a week, as assessed by Trypan blue assay (data not shown). To assess the possible impact of IFN-β on stem cell differentiation, we analyzed GS-2, 5, 7, and 9 cells for changes in the expression of different stem cell markers. GS-2 and GS-9 cells expressed CD133, but expression remained unchanged after exposure to 150 IU/mL IFN-β for 48 hours. GS-5 and GS-7 did not express CD133 (Fig. 2G). Moreover, IFN-β–treated GS-2, GS-5, and GS-9 cells showed no changes of GFAP, nestin, β-III-Tubulin, or CNPase staining (shown for GS-2; Fig. 2H).

Requirement for IFNAR-1 and IFNAR-2 for IFN-β–mediated sensitization to irradiation and temozolomide
To verify the role of IFNAR-1 and IFNAR-2 for IFN-β–mediated signal transduction and sensitization to temozolomide and irradiation, we silenced the expression of both receptors by siRNA. Efficacy of gene silencing was assessed by qPCR for IFNAR-1, which could not be assessed by flow cytometry (Fig. 1), and by qPCR and flow cytometry for IFNAR-2 (Fig. 3A). In the setting of temozolomide exposure (Fig. 3B) or irradiation...
Figure 1. IFNAR-1 and -2 expression and responsiveness to IFN-β in human LTL and GIC. A and B, the cells were assessed for expression of IFNAR-1 and IFNAR-2 mRNA by PCR with GAPDH as control (A) and of protein by cell surface flow cytometry (B, left; representative profiles for K562 as a positive control and LNT-229, LN-18, LN-308, GS-2, and GS-9 GIC cells; black curve, isotype control; gray curve, IFNAR antibody), or immunofluorescence staining (B, right panel; MCF-7 and K562 were used as control). C, phosphorylation levels of STAT-3 in a concentration- (left) and time-dependent (right) manner, shown representatively for LNT-229 cells (top row), and for GS-7 and GS-9 GIC in a time-dependent manner (bottom row). D, responsiveness to IFN-β was assessed through detection of MxA protein in a concentration- (top row) and time-dependent (bottom row) manner, shown representatively for LNT-229 cells.
(Fig. 3C), silencing of IFNAR-1 or -2 or both attenuated the sensitizing effect of IFN-β in LNT-229 cells and LN-18 cells, confirming a role for IFNAR-mediated signal transduction pathways in the IFN-β–induced sensitization process. IFNAR-2 gene silencing alone did not abrogate the effect of IFN-β on temozolomide activity to the same extent as IFNAR-1 gene silencing alone.

**Response to temozolomide, irradiation, and IFN in GIC lines**

Since GIC are proposed to be the major source of tumor relapse and resistance, we next focused on these models. All investigated GIC, except GS-9, expressed MGMT and were highly resistant to temozolomide (Supplementary Note S1 and Supplementary Fig. S1). IFN-β had no major effect on cell density of LTL cells, but a significant concentration–dependent impact of IFN-β alone was observed in GIC cells (Fig. 4A), as expected from the data shown in Fig. 2F. To assess whether IFN-β also partially overcomes temozolomide resistance of GIC, we pre-exposed the cells to increasing concentrations of IFN-β (Fig. 4B, left), or to 150 IU/mL IFN-β for increasing periods of time (Fig. 4B, right), before treatment with temozolomide at EC_{50} concentrations. All investigated GIC lines showed sensitization to temozolomide after pre-exposure to IFN-β. Sensitization was significant in all cell lines when treated at a concentration of 150 IU/mL and for an exposure time of 24 hours. Exposure of GS-2 cells to IFN-β for 24 hours before administration of temozolomide induced a strong growth-inhibiting effect on the sphere cultures (Fig. 4C). IFN-β–treated cells showed a decrease in clonogenic survival exceeding 50% compared with temozolomide only-treated cells, and exhibited a progressive loss of the sphere structure (see also Fig. 2D). Similar effects, albeit with less impressive disaggregation, were observed for GS-5, GS-7, and GS-9 spheres, where cooperative effects were most prominent when IFN-β was given with temozolomide at approximately EC_{50} concentrations.

In the setting of irradiation experiments, GIC cell lines were not more resistant than LTL, with GS-2 displaying the strongest radioresistance of the panel, and GS-5 the weakest, possibly because of the TP53 wild-type status of this cell line (ref. 29; Fig. 4D). Pre-exposure to increasing concentrations of IFN-β followed by low dose irradiation at 1 Gy resulted at least in additive inhibition of clonogenic survival. Again, in the rather radioreistant GS-2, a significant impact of IFN-β alone was observed (Fig. 4E, left); preexposure to IFN-β before irradiation led to a reduction of cell density fulfilling criteria of synergy, with an additional reduction of cell density of almost 50% when exposed to 150 IU/mL of IFN-β. GS-5 and GS-7 displayed synergistic effects at 150 IU/mL IFN-β; no synergy was determined in GS-9 (Fig. 4E).

**Gene expression analyses**

Microarray-based gene expression profiling demonstrated IFN-β–dependent significant differential regulation of 509 genes after 6 hours of IFN-β treatment in all three glioma cell lines investigated. Gene expression profiling after 24 hours revealed significant differential regulation of 522 genes. The combined analysis, comparing the 6- and 24-hour data, resulted in an overlap of 132 differentially expressed genes upon exposure to IFN-β in all three cell lines. In addition to the statistical analysis, where IFN-β treatment effects were studied globally across all three cell lines, the impact of IFN-β was assessed individually for every single cell line. Single analysis probe lists of all three cell lines were compared at 6 and 24 hours, respectively (Supplementary Fig. S2), defining overlapping lists of regulated genes as well as lists of genes exclusively regulated in each individual cell line. Multiple transcripts known to be regulated by IFN-β were found, including STAT1, interferon regulatory factors (IRF), and Mx1 (MxA; Supplementary Table S1). Moreover, we noted that a number of genes predicted to promote apoptotic signaling were induced by IFN-β, (Supplementary Table S1), with an overlap of 6 genes annotated to both gene groups. Submission of the differentially expressed IFN-regulated genes to the Search Tool for the Retrieval of Interacting Genes/Proteins (STRING) identified a single main cluster of genes with strong interaction profile (Supplementary Fig. S3A). Submission of the differentially expressed apoptosis-related genes revealed 3 main clusters, one cluster involving tumor necrosis factor-related apoptosis-inducing ligand (TRAIL/TNFSF10)-interacting genes (yellow), one involving XIAP-associated factor 1 (XAF1)-interacting genes (blue), both connected via a third cluster centered around STAT1 (green; Supplementary Fig. S3B). Induction of TRAIL and XAF1 was confirmed by qPCR and immunoblot analysis (Fig. 5). As we had observed differential reaction of the LTL cell line LNT-229 and the GIC cell lines GS-2 and GS-9 in clonogenic growth assays after exposure to IFN-β alone, we performed a gene ontology (GO) analysis of the genes exclusively regulated (FC > 2) in LNT-229, or the GIC lines (Supplementary Fig. S2, peripheral regions), and identified several downregulated genes involved in proliferation and cell growth as well as upregulated genes involved in negative regulation of proliferation or cell-cycle arrest (Supplementary Table S2). Notably, more genes were regulated in the GIC lines, with 2 main clusters of negative regulators of proliferation interacting mainly through JUN (blue cluster) and IL-8, IL-6, and JAK2 (red cluster; Supplementary Fig. S3C).

**Altered expression of apoptosis-regulating genes does not mediate enhanced clonogenic cell death induced by temozolomide or irradiation**

To define a role for altered expression of apoptotic machinery genes in the biologic effects of IFN-β, we examined whether IFN-β alone or when combined with different death stimuli promoted caspase activation under the conditions that induced synergistic inhibition of clonogenic survival (Fig. 4). As a positive control, we used MFL since we previously observed IFN-α–induced sensitization to CD95L although the mechanism remained
Figure 2. Assessment of IFN-β effects on GIC cells. A and B, LTL or GIC cells were exposed to IFN-β at 150 IU/mL for 24 hours, cultured for an additional 48 hours in serum-enriched medium, and flow cytometric cell-cycle analysis (A) or Annexin (AnxV)/PI flow cytometry (B) was performed. Cell distributions are shown as bar graphs (striped, sub-G1; black, G1; white, S; gray, G2–M). Cell lines in B match those shown in A. C, LNT-229 or GS-2 cells were exposed to IFN-β (150 IU/mL), ddH2O aqua (negative control) or salinomycin (SAL; 4 μmol/L; positive control) for 24 hours. D, LNT-229 and GS-2 cells were treated as in C for protein lysates and assessed for LC3 A/B cleavage. GAPDH was used as control. E, the effect of IFN-β (150 IU/mL, 24 hours) on sphere formation over a range of 5–10,000 single cells was assessed by sphere count and is shown for GS-2 (black square, IFN-β; white diamond, vehicle). Data, mean ± SEM (n = 6; ***, P < 0.001). (Continued on the following page.)
unclear then (35). MFL, but neither IFN-β nor temozolomide, induced the cleavage of caspases 8 or 3 or DEVD-amc-cleaving caspase activity (Fig. 6A–C). Similar results were obtained for irradiation assays (data not shown). Preexposure to IFN-β did not result in caspase processing in cells exposed to temozolomide either. Cell death in the investigated settings was confirmed by Trypan blue dye exclusion (Fig. 6D). Finally, we performed clonogenic cell death assays similar to those in Fig. 4 in the absence or presence of the broad-spectrum caspase inhibitor, zVAD-fmk, to explore whether caspase inhibition attenuated or abrogated the effects in clonogenic cell death assays of IFN-β or temozolomide alone or in combination (Fig. 6E). These assays confirmed the absence of a role for caspases,
either upon single agent exposure or combination. The biologic activity of zVAD-fmk under these conditions was confirmed by the inhibition of death receptor-mediated apoptosis as previously reported (36).

Discussion

Even after the implementation of temozolomide as the first active chemotherapeutic agent when combined with standard radiotherapy, glioblastomas remain a major challenge in the field of neuro-oncology as they often relapse early and follow an invariably fatal clinical course. The latter is also true for the subgroup of patients with MGMT promoter methylation who derive most benefit from temozolomide (4, 6). Large efforts have been made to improve prognosis by investigating new agents, either at recurrence, but recently more often in development already in the paradigm of concomitant and adjuvant temozolomide plus radiotherapy (3, 37, 38).

Here we asked whether the immune modulatory cytokine, IFN-β, acts on glioma LTL and GIC lines, and sensitizes for the anticlonogenic effects of temozolomide or irradiation. We detected the expression of IFNAR-1 and -2 mRNA in all glioma cells, making them a potential target for IFN-β (Fig. 1A). Although detection of IFNAR-1 protein turned out to be challenging and was possible by immunofluorescence microscopy only, but not by flow cytometry, the biologic effects of IFNAR-1 gene silencing were prominent: siRNA-mediated knockdown of the single IFNAR-1 chain inhibited IFN-β-mediated sensitization (Fig. 3), thereby confirming its biologic function. Silencing of the IFNAR-2 chain alone inhibited IFN-β signaling only to a moderate level whereas silencing of IFNAR-1 was additionally required to abort the intracellular signal cascade enough to lead to a highly significant

Figure 4. GIC sensitization to temozolomide and irradiation by IFN-β. A, LTL or GIC cells were exposed to IFN-β in a concentration-dependent manner and clonogenic survival was assessed by crystal violet (LTL) or MTT (GIC) assay. B, LTL or GIC cells were exposed to IFN-β in a concentration-dependent (left) or time-dependent (right) manner before a 24-hour pulse of temozolomide in an EC50 concentration range. Clonogenic survival was assessed by crystal violet or MTT assay. C, GS-2, GS-5, GS-7, or GS-9 cells pre-exposed to IFN-β (150 IU/mL, 24 hours) were treated with temozolomide as shown in Fig. 3A and allowed to grow in neurobasal medium for 2 weeks before the assessment of clonogenicity by MTT assay (control: white bar; IFN-β: black bar). Data, mean ± SEM (, P < 0.05; †, P < 0.01; ‡, P < 0.001), for the effect of IFN-β + temozolomide versus temozolomide alone. D, GS-2, GS-5, GS-7, or GS-9 cells were irradiated at 1, 3, or 5 Gy and monitored for clonogenic survival. Cell density was assessed by MTT assay after 2 weeks. E, GS-2, GS-5, GS-7, or GS-9 cells were pre-exposed to increasing concentrations of IFN-β for 24 hours and subjected to irradiation with 1 Gy. Cell density was assessed after 2 weeks of clonogenic growth in neurobasal medium by MTT assay. Data, mean ± SEM normalized to untreated cells (, P < 0.05; †, P < 0.01; ‡, P < 0.001), relative to nonirradiated cells; +, synergistic values, defined as >10% difference between observed and predicted effect. Data (for A, B and D), mean ± SEM (n = 3), P < 0.05; ††, P < 0.01; ‡‡, P < 0.001) relative to untreated cells.

Figure 5. Gene clusters induced by IFN-β. The proapoptotic proteins XAF-1 and TRAIL were assessed by qPCR for RNA and by immunoblot for protein at 6 and 24 hours after exposure to IFN-β in increasing doses (time points as assessed by microarray profiling), in LNT-229 (left) and GS-2 (right).
Figure 6. Role of apoptosis-regulatory genes in IFN-β-induced sensitization. A and B, Immunoblots were performed after exposure of LNT-229 (left) or GS-2 (right) to IFN-β for 6 hours (top row) or 24 hours (bottom row) and the levels of caspases 8 and 3 were assessed either for IFN-β exposure alone, temozolomide alone, or in combination as described. MFL and STS were used as a positive control (MFL: 1 μg/mL; STS: 1 μmol/L). C, DEVD-amc cleaving assays were performed after 6 hours of exposure (shown for 2-hour fluorescence measurement). D, cell death was assessed by Trypan blue exclusion after 6 hours of exposure to IFN-β at 150 or 300 IU/mL, IFN-β + temozolomide (10 μmol/L for LNT-229, 500 μmol/L for GS-2), or MFL and STS as positive controls, as described in C; ddH2O was used as negative control (white bars, alive cells; black bars, dead cells; normalized to 100% cells). E, clonogenic cell death assays were performed for LNT-229 and GS-2 and analyzed by crystal violet staining (for LNT-229) or MTT assay (for GS-2) at day 10 after exposure to either IFN-β or temozolomide alone, or combinations at indicated concentrations, with or without ZVAD-fmk (15 μmol/L).
reduction in inhibition of clonogenic survival after IFN-β exposure (Fig. 3B and C). This may be due to the fact that while IFNAR-2 holds only ligand-binding capacities, IFNAR-1, mainly inducing the intracellular signaling cascades, has also been described to have weak ligand binding activity, too, and may interact with other proteins in the absence of IFNAR-2 (39, 40). Alternatively, although both siRNA pools reduced receptor mRNA expression to a similar extend (Fig. 3A), differential protein stability may account for different biologic efficiency of gene silencing in these experiments. Responsiveness of the cells was assessed by monitoring the expression of target proteins of the IFN-β signaling pathways (Fig. 1D).

STAT-3 has been shown to be involved in antiproliferative functions when induced by IFN-α/β in human Daudi cells (41) and, in glioma cells, may act as an IFN-β–induced tumor inhibitor through negative modulation of miR-21 (42). Conversely, there is also accumulating evidence that STAT-3 is a driver of the malignant phenotype of glioblastoma (43). In our study, STAT-3 was uniformly phosphorylated in both LTL and GIC cell lines shortly after exposure to IFN-β (Fig. 1C). Thus, the biologic consequences of STAT-3 phosphorylation may be context-dependent and need to be interpreted in the natural course or the therapeutic setting in which they are observed.

Since GIC cells cultured under sphere conditions are considered to be a more resistant subpopulation of glioma cells (44–46), we characterized cell-cycle progression, cell death induction, and sphere formation capacity of GIC in the presence of IFN-β. Similar to LTL, we observed a cell-cycle arrest with a reduced G1 phase and an increase of the sub-G1 population, reflecting a moderate increase in the necrotic fraction on Annexin V/PI flow cytometry (Fig. 2A and B). Exposure of singularized cells isolated from sphere cultures to IFN-β led to reduced sphere formation; moreover, fully formed spheres exposed to IFN-β for 24 hours disaggregated in the first days (Fig. 2E and F), and the cells underwent delayed cell death after more than a week as assessed by Trypan blue dye exclusion (data not shown). This sphere disruption effect with delayed cell death induction appears to be a major effect of IFN-β on GIC survival and to play a more important role than early classical apoptotic pathways that were not shown to be activated in the first 48 hours after exposure in Annexin V/PI flow cytometry. Accordingly, Affymetrix array data demonstrated upregulation of several apoptosis-related genes (Supplementary Table S1; Supplementary Fig. S3B), but ZVAD-fmk-controlled clonogenicity assays or DEVD-aml–cleaving assays did again not confirm an induction of classical caspase-determined apoptotic pathways (Fig. 6C and E).

We demonstrated that IFN-β facilitated the loss of clonogenicity induced by the standard chemotherapeutic agent for glioblastoma, temozolomide. Since a sensitizing mechanism mediated through MGMT and TP53 had been described (20), we assessed IFN-β effects on a panel of cells with a heterogeneous pattern of MGMT and TP53 status (Supplementary note S2 and Supplementary Fig. S4A). In our experimental settings, neither TP53 nor the MGMT status was important for the sensitizing effects of IFN-β. Specifically, we did not observe an induction of TP53 expression in cells with TP53 wild-type transcriptional activity (LNT-229) or a downregulation of MGMT expression in MGMT-expressing cells (LN-18) (Supplementary note S2 and Supplementary Fig. S4C and S4D), nor did we observe MGMT- or TP53-associated changes in clonogenic survival assays, where sensitization by IFN-β was achieved independent of MGMT or TP53 status (Supplementary note S2, Supplementary Fig. S4A and S4B). Finally, Affymetrix chip analyses did neither detect induction of TP53 nor downregulation of MGMT in the cell line expressing the respective gene products (TP53: LNT-229, G5-2; MGMT: G5-2; data not shown). The sensitization in the presence of MGMT is particularly attractive in view of the urgent clinical need for novel strategies for the majority of glioblastoma patients with tumors without MGMT promoter methylation. Moreover, we confirmed that preexposure to IFN-β sensitized different LTL to the anticolonogenic effects of single doses of irradiation, too (Supplementary Fig. S4B), and that these effects were mediated by the known receptors of IFN-β, IFNAR-1, and IFNAR-2 (Fig. 3).

GIC lines, which were confirmed here to be highly resistant to temozolomide due to MGMT expression, appeared to be a special target to IFN-β which impaired sphere formation when administered alone, in the absence of major cell death induction (Fig. 2).

Interestingly, we observed a growth-inhibiting effect of IFN-β in GIC cultures even when applied as a single agent (Fig. 4A), even in MGMT-expressing and highly temozolomide-resistant models (Fig. 4B–E). These chemosensitizing effects of IFN-β were concentration- and time-dependent, with significant results assessed at a concentration of 150 IU/mL and a 24-hour application (Fig. 4B and E). Of note, the molecular pattern in GIC cells was also diverse with regard to TP53 status (29), confirming that TP53 is not a major mediator of IFN-β–induced sensitization in glioma cells.

All glioma models investigated here were sensitized at concentrations of IFN-β reached in the serum in clinical settings following intravenous application, where ranges of more than 1,000 IU/mL were reported at doses of 18 × 10⁶ IE i.v. in healthy volunteers (47–49). IFN-β has been applied intravenously before in several clinical studies and was shown to be well tolerated without significant side effects (50), making it an interesting candidate for adjuvant glioblastoma therapy, close to practice. Thus, the present laboratory evidence, together with the wealth of data on the safety and tolerability of IFN-β in patients with multiple sclerosis, justifies further clinical trials of IFN-β in combination with radiotherapy and temozolomide in patients with newly diagnosed glioblastoma, specifically those patients suffering from MGMT-unmethylated tumors.

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C. Happold is a consultant/advisory board member for MSD. P. Roth is a consultant/advisory board member for MSD, Roche, and Molecular Partners. G. Reifenberger has received honoraria from the speakers’ bureau of Merck Serono. M. Weller has commercial research grants from Bayer, Antisense Pharma, Merck Serono, and Roche; has received honoraria from the speakers’ bureaus of MSD, Roche, and Merck Serono; and is a consultant/advisory board member for Magforce. No potential conflicts of interest were disclosed by the other authors.

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