The G Protein–Coupled Receptor GALR2 Promotes Angiogenesis in Head and Neck Cancer

Rajat Banerjee\(^1\), Elizabeth A. Van Tubergen\(^1\), Christina S. Scanlon\(^1\), Robert Vander Broek\(^1\), Joel P. Lints\(^1\), Min Liu\(^1\), Nickole Russo\(^1\), Ronald C. Inglehart\(^1\), Yugang Wang\(^1\), Peter J. Polverini\(^1\), Keith L. Kirkwood\(^3\), and Nisha J. D’Silva\(^1,2\)

Abstract

Squamous cell carcinoma of the head and neck (SCCHN) is an aggressive disease with poor patient survival. Galanin receptor 2 (GALR2) is a G protein–coupled receptor that induces aggressive tumor growth in SCCHN. The objective of this study was to investigate the mechanism by which GALR2 promotes angiogenesis, a critical oncogenic phenotype required for tumor growth. The impact of GALR2 expression on secretion of proangiogenic cytokines in multiple SCCHN cell lines was investigated by ELISA and in vitro angiogenesis assays. Chemical inhibitor and genetic knockdown strategies were used to understand the key regulators. The in vivo impact of GALR2 on angiogenesis was investigated in mouse xenograft, chick chorioallantoic membrane, and the clinically relevant mouse orthotopic floor-of-mouth models. GALR2 induced angiogenesis via p38-MAPK-mediated secretion of proangiogenic cytokines, VEGF, and interleukin-6 (IL-6). Moreover, GALR2 activated small-GTP-protein, RAP1B, thereby inducing p38-mediated inactivation of tristetraprolin (TTP), which functions to destabilize cytokine transcripts. This resulted in enhanced secretion of proangiogenic cytokines and angiogenesis in vitro and in vivo. In SCCHN cells overexpressing GALR2, inactivation of TTP increased secretion of IL-6 and VEGF, whereas inhibition of p38 activated TTP and decreased cytokine secretion. Here, we report that GALR2 stimulates tumor angiogenesis in SCCHN via p38-mediated inhibition of TTP with resultant enhanced cytokine secretion. Given that p38 inhibitors are in clinical use for inflammatory disorders, GALR2/p38-mediated cytokine secretion may be an excellent target for new adjuvant therapy in SCCHN. Mol Cancer Ther; 13(5); 1–11. ©2014 AACR.

Introduction

Each year nearly 600,000 individuals are diagnosed with squamous cell carcinoma of the head and neck (SCCHN), which is the sixth most common cancer globally (1). Despite treatment, almost half of the patients die of disease within 5 years of diagnosis (1). Elucidating the mechanisms that support tumor progression will facilitate the development of mechanism-based treatment strategies. Angiogenesis has a critical role in tumor progression (2, 3). For example, the vasculature provides nutrients and oxygen to the tumor as well as an avenue to eliminate metabolic waste and CO\(_2\) (3). Continuous neovascularization facilitates tumor growth and spread (2).

In SCCHN, angiogenesis is activated by cytokines, including interleukin-6 (IL-6) and VEGF (4, 5). IL-6 is a biomarker for poor disease-specific survival (6) and high VEGF correlates with reduced time-to-disease recurrence (7). Inhibitors to IL-6 and VEGF were developed to target the vasculature of multiple solid tumors (8). However, though VEGF inhibitors are used as an adjuvant to chemotherapy in colorectal cancer, the drug does not prevent disease recurrence (9). In breast cancer, VEGF inhibitors only marginally improved survival, possibly due to redundancy in function between cytokines. In fact, approval of VEGF inhibitors for treatment of breast cancer was recently revoked (10).

IL-6 and VEGF are regulated posttranscriptionally to enable rapid modulation of protein expression (11). mRNA is actively degraded or stabilized by RNA-binding proteins (RNA-BP) that bind AU-rich elements in the 3’untranslated region (UTR). Tristetraprolin (TTP) is an RNA-BP that promotes decay of transcripts of proangiogenic factors, including IL-6, VEGF, and IL-8, in cancer and inflammatory cells (6, 12, 13). Downregulation of TTP in SCCHN leads to transcript stability and enhances secretion of IL-6 and VEGF (6) but its role in tumor angiogenesis has not been investigated.
p38-MAPK is a critical signaling molecule that activates cytokines. In SCCHN and multiple myeloma, p38 is constitutively active and promotes tumor growth, survival, and invasion by modulating secretion of multiple cytokines and proinflammatory mediators (14) but its role in angiogenesis is unexplored.

Human galanin (GAL), a 30 amino acid neuropeptide, promotes pain, nociception, and cell survival in the central and peripheral nervous systems (15). GAL is secreted by nonneuronal cells, such as keratinocytes, including malignant keratinocytes (16, 17). GAL induces its biologic effects via three G protein–coupled receptors (GPCR), galanin receptors GALR1, GALR2, and GALR3 (18). Only GALR1 and GALR2 have been linked to tumorigenesis in nonneuronal cells (19). GALR1 is frequently silenced in SCCHN and has a tumor-suppressive effect (17, 20), whereas GALR2 promotes tumor proliferation and survival (16). GALR2 is unchanged or overexpressed in SCCHN compared with normal human keratinocytes (16, 21). Even without a change in expression, GAL-induced GALR2 signaling may be amplified by concurrent downregulation of GALR1 (21).

A previous study showed that GALR2 induces angiogenesis during wound healing (22) but its role in tumor angiogenesis was unknown. Using small cell lung cancer cell lines, Yamamoto and colleagues (23) recently showed that GAL stimulates angiogenesis but the signaling cascade was uncharacterized. In the present study, we show that GAL induces angiogenesis via GALR2-induced, RAP1B-p38-mediated IL-6 and VEGF secretion. RAP1B, a ras-like protein, shuttles between inactive GDP- and active GTP-bound forms. Given the importance of proangiogenic cytokines such as IL-6 and VEGF in tumor progression, inhibition of secretion of these factors by targeting a common upstream regulator may be a promising strategy to suppress angiogenesis and tumor progression.

Materials and Methods

Cell culture

SCCHN cell lines (T. Carey, University of Michigan, Ann Arbor, MI) were cultured as described and validated by genotyping at the Sequencing Core (University of Michigan) before and at the end of the study (24, 25). An immortalized human microvascular endothelial cell line (HMEC-1; Center for Disease Control) was used for sprouting assays. HMEC-1 cells were maintained in MCDB-131 media (Gibco) supplemented with 10% FBS, 1% glutamine, 1% penicillin/streptomycin, and 1 ng/mL EGF.

Conditioned medium

Conditioned medium (CM) was collected as described (6). Briefly, SCCHN cells at approximately 60% to 70% confluence were cultured in Dulbecco’s Modified Eagle Medium (DMEM) without supplements. After 24 hours, the medium was centrifuged and the supernatant (conditioned medium) was collected and concentrated using 3 kDa centrifugal filters (Millipore).

Transfection and knockdown

For transient knockdown of p38, ON-target-SMART-pool siRNA (Dharmacon) was used. To downregulate TTP and IL-6, four siRNAs were screened for each target; siRNAs yielding optimal, sustained knockdown were used (26). Transfections were performed as described (6). UM-SCC-1 and UM-SCC-81B cells were stably transfected with pcDNA3.1-GALR2 or pcDNA3.1 as described (16).

For stable knockdown of TTP, UM-SCC-1 and -81B cells were transduced with short hairpin RNA (shRNA) shTTP and shControl (scramble) in lentiviral particles (Open Biosystems; ref. 26). For stable knockdown of VEGF in UM-SCC-1-GALR2 cells, cells were transduced with shVEGF (Open Biosystems). Stable cell lines were selected in 10 μg/mL puromycin (Sigma).

Western blot analysis

Cell lysates were electrophoresed (6) and incubated with primary antibodies (concentration 1:1000 unless otherwise indicated): phospho-p38 (p–p38), total p38 (p38), actin, RAP1B (Cell Signaling Technology), TTP (Santa Cruz Biotechnology), p-Serine (Abcam), IL-6 (R&D Systems), GALR2 (Alpha Diagnostics), and glyceraldehyde-3-phosphate dehydrogenase (GAPDH; Millipore/Upstate). Horseradish peroxidase-conjugated secondary antibodies (Jackson ImmunoResearch) were visualized by SuperSignal Substrate (Pierce).

Immunoprecipitation

TTP was immunoprecipitated with TTP antibody (Santa Cruz Biotechnology) crosslinked to Amino-Link Plus Coupling Resin (Pierce) supplemented with protease (Roche) and phosphatase (Sigma) inhibitors.

ELISA

IL-6 and VEGF-A were quantified by noncompetitive ELISA (R&D Systems).

Endothelial tube formation (sprouting) assay

Growth factor-depleted Matrigel (BD Biosciences) was coated on a chamber slide (BD Biosciences) as described (27). Conditioned medium was normalized to cell number and volume, and resuspended in MCDB-131 media containing 3% FBS. HMEC-1 cells (4 x 10⁴) were seeded in triplicate in 150 μL of conditioned medium from cells transfected with nontarget (NT), sip38, siTTP, or siIL-6. VEGF (1 ng/mL) was used as a positive control in initial experiments (not shown). DMEM served as a negative control. Digital images of endothelial tubes were taken after 24 hours (five random fields/well). Endothelial tubes were counted in each field to determine tube number. Tube length was determined with ImageJ software using arbitrary units.

GALR2 studies

For activation studies, UM-SCC-1-GALR2 and -pcDNA cells were serum starved for 4 hours and treated with...
10 nmol/L GAL (Sigma) as described (16). For inhibition studies, UM-SCC-1-GALR2 cells were incubated with GALR2-specific antagonist M871 (Tocris Bioscience, 100 nmol/L) with dimethyl sulfoxide as control.

**Inhibition of p38-MAPK**

Cells were serum starved for 4 hours and incubated with 10 μmol/L of SB203580 (Promega) for 1 hour.

**In vivo studies and immunohistochemistry**

All in vivo studies were done according to University of Michigan University Committee on Use and Care of Animals (UCUCA)-approved protocols. UM-SCC-1-GALR2 and -pcDNA (1×10⁶) were injected subcutaneously (n = 10, 5 in each group) in athymic mice (Ncr nu/nu strain, National Cancer Institute, Frederick, MD) for tumor growth as reported (16). Angiogenesis of the tumor was quantified by measuring vascular density (redness) normalized to surface area with ImageJ software. For the clinically relevant floor-of-mouth xenograft model of SCCHN, UM-SCC-81B-shTTP and control cells (1×10⁶) were implanted submucosally in the floor-of-mouth of athymic mice (28). Immunohistochemistry was performed on tissue sections for pancytokeratin (Millipore; ref. 29) and Factor-VIII (DAKO).

**Chicken CAM**

Cells were seeded on the chick chorioallantoic membrane (CAM), an in vivo model of angiogenesis in SCCHN (30). AngioTool (https://ccrod.cancer.gov/confluence/display/ROB2/Home) was used to quantify the vasculature.

**Statistical analysis**

Statistical analysis was performed using a Student t test. P < 0.05 was considered to be statistically significant. Densitometry was performed using ImageJ software.

**Results**

**GALR2 induces angiogenesis**

Previously, we showed that overexpression of GALR2 in multiple SCCHN cell lines induces proliferation and survival in vitro and aggressive tumors in the mouse (16). In the present study, we show that tumors generated from UM-SCC-1-GALR2 cells are more vascular than control tumors in the mouse. As shown in Fig. 1A, the UM-SCC-1-GALR2 tumors are more reddish-brown than control tumors, compatible with more vascularity (left panel and graph). Increased vascularity was verified by immunostaining with Factor-VIII on tissue sections. Blood vessels, which stained positively for Factor-VIII, increased by 2-fold in UM-SCC-1-GALR2 compared with control tumors (Fig. 1A, middle right and right, respectively). The microscopic appearance and cytokeratin immunoreactivity of the tumors were consistent with SCCHN. Immunoglobulin G controls were appropriately negative (not shown).

To independently verify the angiogenic potential of GALR2 in SCCHN, we used the CAM model (30). UM-SCC-1-GALR2 cells seeded on the CAM induced larger, more angiogenic tumors than control UM-SCC-1-pcDNA cells (Fig. 1B, left), consistent with mouse studies (Fig. 1A; ref. 16). Around the tumor, the vascularity (Fig. 1B, middle left), as quantified by branching points (white arrowheads), and length of blood vessels (white arrows) were higher in UM-SCC-1-GALR2 compared with control tumors (Fig. 1B, middle right graphs). Corresponding tissue sections of the CAM showed more vasculature in UM-SCC-1-GALR2 tumors than controls (Fig. 1B, right). Similar results were observed with UM-SCC-81B-GALR2, an independent SCCHN cell stably overexpressing GALR2 (Supplementary Fig. S1A and S1B). Consistent with a role for GALR2 in angiogenesis, the GALR2-specific inhibitor M871 reduced vascularity in vivo (Supplementary Fig. S2). To verify whether the enhanced vascularity is mediated by cytokines secreted from tumor cells, in vitro sprouting assays were performed. Endothelial cells (HMEC-1) were incubated with conditioned media from UM-SCC-1-GALR2 or control cells. The number and length of tubes (arrows) were increased in HMEC-1 cells that were incubated with conditioned medium from UM-SCC-1-GALR2 cells (Fig. 1C, middle-left panel and graphs). GALR2 overexpression was confirmed by immunoblot analysis (Fig. 1C, left, also for UM-SCC-81B-GALR2 in Supplementary Fig. S1B, bottom). The in vitro and in vivo studies support that GALR2 induces angiogenesis, a hallmark of tumor progression.

**GALR2 stimulates cytokine secretion and angiogenesis via RAP1B, p38**

Given the emerging importance of p38 in angiogenesis (3), the role of GALR2 in p38 stimulation was investigated. To do so, endogenous GALR2 was downregulated in UM-SCC-1 cells (Supplementary Fig. S3). Loss of GALR2 expression by two siRNAs (siGALR2-7 and siGALR2-10) resulted in downregulation of phospho-p38 (Supplementary Fig. S3), which verifies that p38 is induced by GALR2. In complementary gain-of-function experiments, endogenous p38 activation was observed in UM-SCC-1-GALR2 cells compared with controls (Fig. 2A and B, left also in UM-SCC-81B-GALR2 cells in Supplementary Fig. S1B, top). Moreover, phosphorylation of p38 increased more rapidly in UM-SCC-1-GALR2 cells stimulated with 10 nmol/L GAL compared with control pcDNA cells (Fig. 2A, left).

RAP1B, ras-like protein, is a critical mediator of signaling in SCCHN (16). To investigate the role of RAP1B in GAL-induced p38 activation (Fig. 2A, right), RAP1B was downregulated with siRAP1B in UM-SCC-1-GALR2 cells, which were seeded at equal density and stimulated with 10 nmol/L GAL. GAL-induced p38 activation (Fig. 2A, right, lane 2 compared with 1) was inhibited by siRAP1B (Fig. 2A, right, lanes 3 and 4).

To investigate whether GALR2 induces angiogenesis via p38, initial studies focused on whether proangiogenic cytokine secretion is induced by GALR2 via p38. UM-SCC-1-GALR2 cells secrete almost 2-fold more
VEGF and IL-6 than control cells (Fig. 2B, middle and right, respectively), correlating with increased phospho-p38. Importantly, downregulation of p38 in UM-SCC-1-GALR2 cells reduced secretion of VEGF and IL-6 (Fig. 2C) thereby establishing that GALR2 induces cytokine secretion via p38. Similar results were obtained with UM-SCC-81B-GALR2 cells, another SCCHN cell line (Supplementary Fig. S4). In corresponding endothelial tube-formation assays, downregulation of p38 significantly reduced tube number and length (Fig. 2D).

Taken together, GALR2 induces cytokine secretion and endothelial tube formation via RAP1B-mediated p38 activation.

**GALR2 promotes angiogenesis via p38-TTP-mediated cytokine secretion**

We previously showed that p38 phosphorylates TTP, which destabilizes transcripts including matrix metalloproteinases and IL-6 (26). Because GALR2 induces p38 (Fig. 2B), we investigated the extent to which GALR2
induces VEGF and IL-6 via p38-mediated phosphorylation of TTP, using biochemical and RNA interference approaches outlined in Fig. 3A (left). To determine whether GALR2 induces p-TTP via p38, UM-SCC-1-GALR2 cells were stimulated with 10 nmol/L galanin for 4, 10, or 20 minutes. Whole-cell lysates were immunoblotted for phospho-p38 and p38 antibodies, quantified (DU), and expressed as percentage of control (left). UM-SCC-1-GALR2 stable cells were treated with NT-siRNA or si-RAP1B. After 68 hours of transfection, cells were serum starved for 3 hours and were either stimulated with 10 nmol/L galanin or vehicle control for 10 minutes. Both stimulated and unstimulated controls were immunoblotted with actin, RAP1B, p-p38, and p38 antibodies and were quantified (right). B, UM-SCC-1-GALR2 or control cells were immunoblotted with p-p38 and total p38 antibodies (left). Conditioned medium was collected and VEGF and IL-6 were quantified with ELISA as pg/mL/million cells and were finally expressed with normalization to control (right; *, P < 0.014). C, UM-SCC-1-GALR2 cells were treated with si-p38 or NT-siRNA and were immunoblotted with p38 and total p38 antibodies (left). Conditioned medium was collected and VEGF and IL-6 were quantified (right; *, P < 0.01). D, UM-SCC-1-GALR2 cells were treated with si-p38 or NT-siRNA and were immunoblotted (left). Conditioned medium was collected, concentrated, normalized for equal cell count, and HMEC-1 cells were seeded with corresponding conditioned medium and photographed (middle left). Average number of tubes and tube length was quantified from 10 representative fields (right). Data are representative of three identical experiments each in triplicate (*, P < 0.008).

Figure 2. GALR2 stimulates cytokine secretion and angiogenesis via RAP1B-p38-MAPK. A, stable mixed clonal population of UM-SCC-1-GALR2 or control pcDNA cells were serum starved for 4 hours and treated with 10 nmol/L Galanin for 0, 2, 5, or 10 minutes. Whole-cell lysates were immunoblotted for phospho-p38 and p38 antibodies, quantified (DU), and expressed as percentage of control (left). UM-SCC-1-GALR2 stable cells were treated with NT-siRNA or si-RAP1B. After 68 hours of transfection, cells were serum starved for 4 hours and were either stimulated with 10 nmol/L galanin or vehicle control for 10 minutes. Both stimulated and unstimulated controls were immunoblotted with actin, RAP1B, p-p38, and p38 antibodies and were quantified (right). B, UM-SCC-1-GALR2 or control cells were immunoblotted with p-p38 and total p38 antibodies (left). Conditioned medium was collected and VEGF and IL-6 were quantified with ELISA as pg/mL/million cells and were finally expressed with normalization to control (right; *, P < 0.014).

C, UM-SCC-1-GALR2 cells were treated with si-p38 or NT-siRNA and were immunoblotted with p38 and total p38 antibodies (left). Conditioned medium was collected and VEGF and IL-6 were quantified (right; *, P < 0.01). D, UM-SCC-1-GALR2 cells were treated with si-p38 or NT-siRNA and were immunoblotted (left). Conditioned medium was collected, concentrated, normalized for equal cell count, and HMEC-1 cells were seeded with corresponding conditioned medium and photographed (middle left). Average number of tubes and tube length was quantified from 10 representative fields (right). Data are representative of three identical experiments each in triplicate (*, P < 0.008).

induces VEGF and IL-6 via p38-mediated phosphorylation of TTP, using biochemical and RNA interference approaches outlined in Fig. 3A (left). To determine whether GALR2 induces p-TTP via p38, UM-SCC-1-GALR2 cells were stimulated with 10 nmol/L GAL in the presence or absence of p38 inhibitor SB203580 (Fig. 3, right). TTP was immunoprecipitated and immunoblotted with phosphoserine and TTP antibodies. GAL induced phosphorylation of TTP by more than 50% (Fig. 3A, right, lane 4 compared with 3), which was abrogated in the presence of SB203580 (Fig. 3A, right, lanes 5 and 6). GAL induced phosphorylation of TTP by more than 50% (Fig. 3A, right, lane 4 compared with 3), which was abrogated in the presence of SB203580 (Fig. 3A, right, lanes 5 and 6), a potent inhibitor of p38-α- and -β catalytic subunits (31).

Phosphorylation of TTP inhibits its ability to target transcripts for degradation thereby enhancing cytokine secretion (26). Therefore, we investigated whether GALR2 induces proangiogenic cytokines via TTP (Fig. 3B).
UM-SCC-1-GALR2 cells transfected with NT-siRNA or siTTP were incubated with SB203580 or vehicle. Compared with baseline, the p38 inhibitor, which increases functional TTP, reduced expression and secretion of VEGF in cell lysate (Fig. 3B, left, lanes 1 and 2) and conditioned medium (middle graph, bars 1 and 2), respectively. In contrast, siTTP enhanced VEGF expression (Fig. 3B, left, lanes 1 and 3) and secretion (middle graph, bars 1 and 3). As expected, siTTP inhibited the effect of SB203580; there is no significant difference between VEGF

Figure 3. GALR2 induces p38-mediated inhibition of TTP to enhance angiogenesis. A, schematic representation of signaling pathway showing GALR2-mediated phosphorylation and activation of p38 that inhibits TTP via phosphorylation. Inactivation or genetic loss (by siRNA) of TTP prevents cytokine degradation giving rise to overall steady state increase in cytokines and acts as angiogenic switch to tumor growth. Chemical inhibitor (SB203580) to p38 kinase activity can dephosphorylate TTP to its active form and degrade cytokines. Alternatively targeting individual cytokines by siRNA could be used to control this angiogenic signal. Upstream inhibitors to angiogenesis might be a better treatment option (left). UM-SCC-1-GALR2 cells were serum starved for 4 hours and then treated with 10 μmol/L of SB203580 for 2 hours and were then stimulated with 10 nmol/L galanin for 10 minutes or vehicle control. Clarified cell lysates were immunoprecipitated with TTP antibody, and blotted with anti-TTP and anti-phospho-kinase antibodies (right). B, UM-SCC-1-GALR2 cells were transfected with siTTP or NT-siRNA and were treated with 10 μmol/L of SB203580 or vehicle control. Cell lysates were immunoblotted with VEGF, IL-6, TTP, and actin antibodies (left). Conditioned medium was collected from each of the treatment groups and ELISA was performed for VEGF and IL-6 (right) and was finally normalized to control. C, UM-SCC-1-GALR2 cells were transduced with shVEGF and control shRNA lentiviral particles and immunoblotted with VEGF antibody and GAPDH. In vitro tubule formation assay was performed with HMEC-1 cells incubated with corresponding conditioned medium collected from cells. Both average and relative number of tubes were quantified from 10 representative fields (, P < 0.02). D, IL-6 was transiently downregulated in UM-SCC-1-GALR2 cells with si-IL-6 and immunoblotted (left) and similarly in vitro tubule formation assay was performed with conditioned medium collected from cells (middle left) and quantified (right; , P < 0.02). Data are representative of three identical experiments in triplicate.
expression (left, lanes 1 and 4) and secretion (middle graph, bars 1 and 4) compared with baseline. Similar results were observed for IL-6 but the impact of siTTP was more profound on IL-6 secretion (Fig. 3B, right graph) than cellular expression (Fig. 3B, left; immunoblot analysis for IL-6), possibly due to rapid secretion of IL-6 (32). Knockdown of TTP was verified (Fig. 3B, left).

Given that GALR2 promotes angiogenesis (Fig. 1) and induces secretion of multiple cytokines, (Fig. 2) we verified that GALR2 induces angiogenesis via VEGF and IL-6. VEGF was stably downregulated by shRNA to VEGF and control in UM-SCC-1-GALR2 cells (Fig. 3C, left). Endothelial Sprouting was quantified after incubation with conditioned medium collected from shVEGF and shControl cells (Fig. 3C, middle left). Tube length and number were significantly reduced by 50% in the UM-SCC-1-GALR2-shVEGF compared with UM-SCC-1-GALR2-shControl (Fig. 3C, graphs). Loss-of-function experiments with siIL-6 in UM-SCC-1-GALR2 had a similar effect and also decreased endothelial sprouting (Fig. 3D).

Suppression of TTP promotes angiogenesis

Because GALR2-mediated phosphorylation of TTP induces proangiogenic cytokines (Fig. 3B and C), TTP's role in angiogenesis was investigated. Conditioned media collected from UM-SCC-1 cells transfected with siTTP or NT-siRNA were used in sprouting assays. Downregulation of TTP was verified (Fig. 4A, left). Endothelial tube formation and length were increased 2-fold by siTTP compared with NT-siRNA (Fig. 4A, middle-left panel and right graphs). To further investigate the effect of TTP knockdown on IL-6, IL-6 was downregulated in UM-SCC-1-shTTP cells. Within 36 hours, downregulation of IL-6 (Fig. 4B, left) inhibited endothelial tube formation (Fig. 4B, middle-left panel and right graphs). The impact of TTP suppression on tumor angiogenesis in vivo was investigated on the CAM. A significant increase in vascularity (white arrows) and branching points (white arrowheads) was observed with UM-SCC-1-shTTP compared with control cells (Fig. 4C, left). Corresponding CAM tissue sections showed greater vascularity in UM-SCC-1-shTTP than control tumors (Fig. 4C, middle right and right, respectively).
Downregulation of TTP induces angiogenesis in vivo

From our previous study (28), human UM-SCC-81B cells induce tumor growth in the floor-of-mouth murine model and recapitulate human SCCHN progression. Therefore, this cell line was used for mouse studies. Initially, we verified that siTTP in UM-SCC-81B induced angiogenesis in vitro. As observed with UM-SCC-1, siTTP in UM-SCC-81B increased endothelial tube number and length by more than 2-fold and 1.5-fold, respectively, compared with control cells (Fig. 5A, middle-left panel and graphs). TTP knockdown was verified (Fig. 5A, left). Knockdown of IL-6 in stable UM-SCC-81B-shTTP cells significantly reduced endothelial tube number and length (Fig. 5B).

Using the murine floor-of-mouth xenograft model (17, 33), we investigated the impact of TTP-mediated angiogenesis on tumor growth in a location commonly involved by human SCCHN. UM-SCC-81B-shTTP and control cells were implanted submucosally in the floor-of-mouth of nude mice (n = 6). Mice were euthanized when moribund and control mice were euthanized concurrently. A representative image of control and test mice bearing tumor (black circle) is shown (left). Sections from the shControl and shTTP tumors were stained with hematoxylin and eosin (H&E) and immunostained with Factor-VIII and cytokeratin antibodies and blood vessels in 10 representative fields were quantified (middle and left; *, P < 0.008). D, summary figure: extracellular GAL stimulates GALR2/RAP1B to induce p38-MAPK to inactivate TTP. Inactivation of TTP inhibits degradation of IL-6 and VEGF mRNA transcripts, thereby causing increased proangiogenic cytokine secretion, angiogenesis, and tumor growth.
clinically detectable tumors in the same time frame (Fig. 5C, left). Histologically, the tumors exhibited SCCHN morphology (Fig. 5C, middle). The epithelial origin of the tumors was verified by immunostaining for pancytokeratin. One of the control mice grew a tumor that was observed on tissue sections although it was not clinically detectable. Immunostaining facilitated visualization and quantification of blood vessels. The average number of blood vessels/10 high-power fields was significantly higher in the tumors generated from UM-SCC-81B-shTTP than control tumors (Fig. 5C, right). Together the in vitro and in vivo data support that downregulation of TTP promotes angiogenesis via release of proangiogenic cytokines.

Discussion

In the present study, we demonstrated that GALR2, a prosurvival GPCR, induces angiogenesis via p38-mediated phosphorylation of TTP and enhanced secretion of VEGF and IL-6. Importantly, the proangiogenic phenotype of GALR2 was observed in vivo in murine tumor xenografts and in the CAM model. This is the first study establishing the role of GALR2 in tumor-associated angiogenesis, a critical phenotype and treatment target in cancer progression.

Angiogenesis, one of the six hallmarks of cancer (3), facilitates tumor progression by supplying oxygen and nutrients. Although GAL expression is correlated with increased microvessel density in inflammatory tissue in the dermis and stimulates angiogenesis in small cell lung cancer cell lines, the role of GALR2 in tumor angiogenesis is unknown (22, 23). In this study, we show that in SCCHN, GALR2 enhances secretion of proangiogenic cytokines, IL-6 and VEGF, and induces angiogenesis via RAP1B-p38-induced inactivation of TTP. SCCHN secretes IL-6 and VEGF, which has been linked with poor patient survival (6, 7, 34). Tumor-derived IL-6 and VEGF promote angiogenesis via paracrine signaling to endothelial cells (35). Knockout of a single VEGF allele in mice is embryonic lethal suggesting that VEGF is critical for maintenance and development of the vasculature (36). To maintain proper vasculature in healthy tissue, there is a delicate balance between angiogenic and antiangiogenic factors; an imbalance in favor of proangiogenic factors promotes tumor growth and spread (37). Therefore, angiogenesis is a promising treatment target to inhibit tumor growth.

Because angiogenesis is critical for tumor progression, drugs targeting either IL-6 or VEGF were developed, but treatment with an individual inhibitor showed marginal improvement in patient survival (38). In phase II clinical trials in patients with breast cancer, concurrent monoclonal VEGF antibody and chemotherapy compared with chemotherapy alone showed little increase in disease-free survival (39). Surprisingly, in mouse studies, short-term treatment with VEGF antibody lead to more aggressive tumors (40). The possibility of redundancy in function of proangiogenic cytokines suggests that it would be beneficial to identify proteins that target multiple cytokines concurrently. In the present study, we show that GALR2 promotes secretion of IL-6 and VEGF and inhibition of GALR2 using a small molecule, leads to inhibition of angiogenesis.

Previously, we showed that GALR2 induces other oncogenic phenotypes, including growth and cell survival, via the extracellular signal-regulated kinase (ERK) and Akt pathways, respectively (16). In this study, we show that GALR2 promotes cytokine secretion and angiogenesis via GALR2-RAP1-p38MAPK-mediated inactivation of TTP. Induction of multiple oncogenic phenotypes by GALR2 may be via induction of multiple signaling pathways. For example, in lung cancer cells, GALR2 induces diverse signaling via three different G-proteins, Gi, Gq, and G12 (41). Because GALR2 also induces tumor growth and cell survival in SCCHN (16), targeting GALR2 may inhibit angiogenesis and other oncogenic phenotypes.

p38 is critical for induction of inflammatory pathways (42) and is constitutively active in SCCHN (42). p38-MAPK is stimulated by IL-1β, in different cell types (26, 43). Previously, we showed that IL-1β-induced p38 promotes transcript stability and secretion of IL-6, prostaglandin E (PGE₂), and VEGF (5). Although macrophages, tumor cells, and cells in the tumor microenvironment secrete IL-1β to stimulate p38, tumor-derived GAL may also induce p38. In addition, exposure to sodium pyruvate phorbol-12-myristate-13-acetate, a potent tumor promoter, induces proinflammatory secretion via p38 activation (42). p38 inhibitors were used with some success in the treatment of inflammatory diseases to limit adverse sequelae and may be a potential adjuvant therapy in SCCHN. p38 inhibitors reduced tumor size in multiple myeloma (44), which may be attributed to reduced IL-6 secretion (45). In our study, we successfully used the p38 inhibitor SB203580 to reduce cytokine secretion.

In SCCHN, we showed recently that p38-MAPK phosphorylates (inactivates) TTP thereby stabilizing cytokine transcripts, secretion, and invasion (26). TTP binds to the 3′UTR of VEGF, IL-6, and PGE₂ transcripts to promote degradation (26). Given the conservation of this region in multiple cytokines, it is likely that other VEGF isoforms are upregulated by the GALR2-induced cascade. VEGF-C promotes lymphangiogenesis thereby contributing to metastasis to lymph nodes (46, 47), which is an important issue for oral cancer spread. VEGF and IL-6 are also transcriptionally regulated by NF-κB, AP-1, and NF-κB (48). There is also convincing evidence that VEGF is regulated by mTOR and hypoxia-inducible factor (49). The present study establishes an additional key upstream regulatory pathway, GALR2-RAP1-p38, in cytokine secretion.

RAP1 is a small GTP-binding protein that is emerging as a significant signaling molecule in SCCHN. In previous studies, we showed that RAP1 mediates ERK and Akt activation (16). In the present study, we showed that RAP1...
induces p38. Although RAP1 may induce multiple signaling cascades, the diversity may also be due to variation in RAP1 isoforms (24). We are currently investigating this possibility.

We and others have shown that GALR2 is expressed in multiple SCC cell lines, including UM-SCC-1, -22B, and -11A; refs. 17, 21, 50. Our current and previous studies established GALR2 expression via both real-time PCR and immunoblot analysis (16, 28). A study performed solely in UM-SCC-1 detected GALR2 transcript (50) but subsequent reports from the same group stated that GALR2 is not expressed in SCCHN (51, 52). The antiproliferative and antiapoptotic roles for GALR2 shown in these studies may be due to the high concentrations of GAL (1 μmol/L), which do not replicate in vivo conditions where GAL is present at nanomolar or lower concentrations (53). For this and previous studies (16), we used physiologic doses of GAL and consistently show that GALR2 promotes proliferation, cell survival, and angiogenesis. Moreover our in vitro and in vivo studies were performed in multiple validated SCCHN cell lines, using complementary overexpression and knockdown approaches. Recently, Misawa and colleagues, (54) showed that GALR2 is silenced expression and knockdown approaches. Recently, Misawa and colleagues, (54) showed that GALR2 is silenced of SCCHN cell lines, using complementary overexpression and knockdown approaches. Recently, Misawa and colleagues, (54) showed that GALR2 is silenced of SCCHN cell lines, using complementary overexpression and knockdown approaches. Recently, Misawa and colleagues, (54) showed that GALR2 is silenced

In summary, our work establishes the importance of GAL/GALR2 in tumor progression via RAP1B-p38-mediated angiogenesis. Because GAL, the ligand for GALR2, is a neuropeptide, our work elucidates an important regulatory mechanism for angiogenesis potentially under the influence of the neuronal system. Given the role of GALR2 in multiple additional oncogenic phenotypes, including growth, survival, and angiogenesis, the GALR2-induced signaling cascade may be an important treatment target in SCCHN.

Disclosure of Potential Conflicts of Interest
No potential conflicts of interest were disclosed.

Authors’ Contributions
Conception and design: R. Banerjee, E.A. Van Tubergen, N.J. D’Silva
Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): R. Banerjee, E.A. Van Tubergen, C.S. Scanlon, R.V. Broek, J.P. Lints, M. Liu, N.J. D’Silva
Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): R. Banerjee, E.A. Van Tubergen, C.S. Scanlon, R.V. Broek, N. Russo, R. Inglehart, N. J. D’Silva
Writing, review, and/or revision of the manuscript: R. Banerjee, E.A. Van Tubergen, C.S. Scanlon, N. Russo, R. Inglehart, Y. Wang, P.J. Polverini, N. J. D’Silva
Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases): J.P. Lints, Y. Wang, K.L. Kirkwood, N.J. D’Silva

Acknowledgments
The authors thank John Westman for assistance in preparing histologic specimens and Tarek Metwallly for CAM data analysis.

Grant Support
This work was supported by National Institute of Dental and Craniofacial Research grants DE018512, DE022567, and DE019513 (to N.J. D’Silva), F30 DE021293 (to C.S. Scanlon), and T32 DE021302 (to E.A. Van Tubergen).

The costs of publication of this article were defrayed in part by the payment of page charges. This article must therefore be hereby marked advertisement in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

Received October 21, 2013; revised February 10, 2014; accepted February 16, 2014; published OnlineFirst February 25, 2014.

References
GALR2-Induced p38-MAPK Promotes Cytokine Secretion and Tumor


www.aacjrournals.org Mol Cancer Ther; 13(5) May 2014 OF11

Published OnlineFirst February 25, 2014; DOI: 10.1158/1535-7163.MCT-13-0904
The G Protein–Coupled Receptor GALR2 Promotes Angiogenesis in Head and Neck Cancer

Rajat Banerjee, Elizabeth A. Van Tubergen, Christina S. Scanlon, et al.

Mol Cancer Ther  Published OnlineFirst February 25, 2014.

Updated version  Access the most recent version of this article at: doi:10.1158/1535-7163.MCT-13-0904

E-mail alerts  Sign up to receive free email-alerts related to this article or journal.

Reprints and Subscriptions  To order reprints of this article or to subscribe to the journal, contact the AACR Publications Department at pubs@aacr.org.

Permissions  To request permission to re-use all or part of this article, contact the AACR Publications Department at permissions@aacr.org.