Identification of Galanin and Its Receptor GalR1 as Novel Determinants of Resistance to Chemotherapy and Potential Biomarkers in Colorectal Cancer

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Abstract

Purpose: A major factor limiting the effective clinical management of colorectal cancer (CRC) is resistance to chemotherapy. Therefore, the identification of novel, therapeutically targetable mediators of resistance is vital.

Experimental design: We used a CRC disease-focused microarray platform to transcriptionally profile chemotherapy-responsive and nonresponsive pretreatment metastatic CRC liver biopsies and in vitro samples, both sensitive and resistant to clinically relevant chemotherapeutic drugs (5-FU and oxaliplatin). Pathway and gene set enrichment analyses identified candidate genes within key pathways mediating drug resistance. Functional RNAi screening identified regulators of drug resistance.

Results: Mitogen-activated protein kinase signaling, focal adhesion, cell cycle, insulin signaling, and apoptosis were identified as key pathways involved in mediating drug resistance. The G-protein–coupled receptor galanin receptor 1 (GalR1) was identified as a novel regulator of drug resistance. Notably, silencing either GalR1 or its ligand galanin induced apoptosis in drug-sensitive and resistant cell lines and synergistically enhanced the effects of chemotherapy. Mechanistically, GalR1/galanin silencing resulted in downregulation of the endogenous caspase-8 inhibitor FLIPL, resulting in induction of caspase-8–dependent apoptosis. Galanin mRNA was found to be overexpressed in colorectal tumors, and importantly, high galanin expression correlated with poor disease-free survival of patients with early-stage CRC.

Conclusion: This study shows the power of systems biology approaches to identify key pathways and genes that are functionally involved in mediating chemotherapy resistance. Moreover, we have identified a novel role for the GalR1/galanin receptor–ligand axis in chemoresistance, providing evidence to support its further evaluation as a potential therapeutic target and biomarker in CRC.

Introduction

Colorectal cancer (CRC) is the second leading cause of cancer-related deaths in Europe and North America. 5-Fluorouracil (5-FU)–based chemotherapy regimens remain the standard treatment for CRC in both the adjuvant and advanced disease settings. However, response rates to 5-FU therapy are between 10% and 20% in the metastatic setting (1). Combining 5-FU with the DNA-damaging agent oxaliplatin has significantly improved response rates for advanced colorectal cancer to 40% to 50%; however, 5-year overall survival remains less than 5% (2). Resistance to chemotherapy, either intrinsic or acquired, ultimately results in treatment failure for the vast majority of patients with metastatic disease and also is a major problem in the locally advanced disease setting, where 40% to 50% patients relapse (3). Therefore, novel therapeutic strategies are urgently required.

The anticancer activities of 5-FU include thymidylate synthase (TS) inhibition and incorporation of its metabolites into RNA and DNA (4). Known determinants of 5-FU response include expression levels of TS and the 5-FU catabolic enzyme dihydropyrimidine dehydrogenase that mediates the degradation of 5-FU (4). Oxaliplatin is a third-generation platinum compound that forms platinum–DNA adducts leading to cytotoxicity. Known determinants of response include expression of excision repair...
Chemotherapy resistance is a major factor limiting effective clinical management of colorectal cancer (CRC). Therefore, the identification of therapeutically targetable mediators of resistance is vital. The aim of this study was to identify potentially druggable targets using a systems biology approach. This resulted in the identification of the receptor-ligand axis, G-protein–coupled receptor galanin receptor 1 (GalR1), and galanin as a novel regulator of drug resistance. Silencing GalR1 or its ligand galanin induced apoptosis in drug-sensitive and drug-resistant cells and synergistically enhanced chemotherapy. Galanin was overexpressed in colorectal tumors and high galanin expression correlated with poor disease-free survival of early stage CRC patients. Collectively, these results show a novel role for GalR1/galanin in chemoresistance, providing evidence to support its further evaluation as a potential therapeutic target and biomarker in CRC.

**Translational Relevance**

Chemotherapy resistance is a major factor limiting effective clinical management of colorectal cancer (CRC). Therefore, the identification of therapeutically targetable mediators of resistance is vital. The aim of this study was to identify potentially druggable targets using a systems biology approach. This resulted in the identification of the receptor-ligand axis, G-protein–coupled receptor galanin receptor 1 (GalR1), and galanin as a novel regulator of drug resistance. Silencing GalR1 or its ligand galanin induced apoptosis in drug-sensitive and drug-resistant cells and synergistically enhanced chemotherapy. Galanin was overexpressed in colorectal tumors and high galanin expression correlated with poor disease-free survival of early stage CRC patients. Collectively, these results show a novel role for GalR1/galanin in chemoresistance, providing evidence to support its further evaluation as a potential therapeutic target and biomarker in CRC.

Materials and Methods

**Materials**

5-FU and oxaliplatin were purchased from Sigma Chemical Co. and Abatra Technology Co Ltd., respectively. zVAD (OMe)-FMK was purchased from Calbiochem. All siRNAs were purchased from Qiagen.

**Cell culture**

Authentication and culture of CRC cell lines HCT116, LS174T, RKO, HT29, SW620, and LoVo have been described previously (15). LS174T (2008), SW620 (2008), and RKO (2001) cells were obtained from the American Type Culture Collection. The p53 wild-type HCT116 human colon cancer cell line kindly provided by Prof. Bert Vogelstein (Johns Hopkins University, Baltimore, MD) in 2003. The 5-FU-, SN-38, and oxaliplatin-resistant HCT116 sublines and the oxaliplatin-resistant p53 null HCT116 subline were generated in our laboratory as previously described (16). The LoVo (2004) cells were obtained from the European Collection of Cell Cultures. RKO and HT-29 human cell lines were provided by the National Cancer Institute. The 5-FU- and SN-38-resistant LoVo and HT29 sublines were generated in our laboratory by continuous exposure of increasing doses of chemotherapy over an 10-month period. The c-FLIPL overexpressing cell lines were previously described (17).

**Patient samples**

Eight patients with metastatic colorectal cancer were included in this study. All patients provided written fully informed consent as per IRB guidelines in the University of Southern California and approval was granted from this body. Patients underwent biopsy of colorectal liver metastases before commencing oxaliplatin/5-FU chemotherapy. CT imaging for response evaluation using WHO criteria was carried out every 6 weeks and patients were subsequently designated as responders, stable disease, or progressive disease. Of these 8 patients, 1 had a partial response to treatment, 3 had stable disease, and 4 had progressive disease on treatment. For the purpose of this study we have further defined “responders” as those patients with either partial response or stable disease and “nonresponders” as those patients with progressive disease.

**Microarray analysis**

Total RNA was extracted from 8 pretreatment metastatic tumor biopsies from patients with advanced colorectal cancer and profiled on the Colorectal Disease Specific Array (DSA) Research Tool (Almac Diagnostics). In addition, in vitro analyses were also carried out using the Colorectal DSA. The in vitro analyses have been previously described for the 5-FU experiment (18) and the same experimental
design was used for the oxaliplatin experiment. Detailed experimental protocols and raw expression data are available at ArrayExpress repository [accession number E-MEXP-3368 (Clinical analysis) and E-MEXP-1691 (in vitro analysis); ref. 19].

Bioinformatic analysis

**Generation of genelists.** All data analysis was completed within Genespring v7.3.1 (Agilent Technologies). All genelists were generated as previously described (6). The filtering criteria used were: (i) all data passing Affymetrix flag calls (P/M) in all samples were retained, (ii) all data passing the cross-gene error model with genes displaying control values greater than the average base/proportional value being retained (this was required in all samples for any gene), (iii) the list was filtered using a 1.5-fold cutoff for each gene relative to the control array, and (iv) all data passing \(P < 0.05\) were retained. All data are displayed as log2 transformed.

For the in vitro analysis, the untreated parental samples were compared with the drug-treated parental samples (inducible parental), the untreated drug-resistant samples were compared with the drug-treated drug-resistant samples (inducible resistant), and the untreated parental cells were compared with the untreated drug-resistant cells (basally deregulated), for both the 5-FU experiment and the oxaliplatin experiment. For the clinical analysis, a genelist was created of those genes that were altered between 5-FU/oxaliplatin experiment. For the clinical analysis, the untreated parental samples were compared with the drug-treated parental samples (inducible parental), the untreated drug-resistant samples were compared with the drug-treated drug-resistant samples (inducible resistant), and the untreated parental cells were compared with the untreated drug-resistant cells (basally deregulated), for both the 5-FU experiment and the oxaliplatin experiment. For the clinical analysis, a genelist was created of those genes that were altered between 5-FU/oxaliplatin responding (PR + SD) and nonresponding patients (PD). No patients achieved a complete response (CR).

**Pathway analysis.** All pathway analysis was carried out using Genespring v7.3.1 (Agilent Technologies) using both KEGG and GenMAPP pathways. Briefly, the final working genelists for both the in vitro experiments and the clinical experiments were used as the starting genelists and pathways were selected that contained greater than 5 genes per pathway. Statistical analysis for each pathway was carried out using hypergeometric statistics.

**Gene set enrichment analysis (GSEA).** GSEA is a computational method for determining whether a rank-ordered list of genes for a particular comparison of interest is enriched in genes derived from an independently generated gene set (20). GSEA was carried out with the expression data set derived from the in vitro samples (inducible parental, inducible resistant, and constitutively altered) and then the clinical samples (responders versus nonresponders). Gene sets from the Molecular Signatures Database (http://www.broad.mit.edu/gsea/msigdb/index.jsp) were used for the enrichment study including the curated gene sets from online pathway databases, publications in PubMed and knowledge of domain experts (C2), and the gene ontology (GO) gene sets (C5). A false discovery rate (FDR) below 25% was considered for significant enrichment.

**RNAi screening**

This was carried out using siRNAs targeting preselected genes identified from microarray analysis. siRNA transfection conditions have been previously described (15). The drugs used were 5-FU \([IC_{30(48 \text{h})}]\) and oxaliplatin \([IC_{30(48 \text{h})}]\). Cell viability was determined by using a 3-(4, 5-dimethylthiazol-2-yl)-2,5-diphenyl tetrazolium bromide (MTT; Sigma) assay as described previously (17). Combination index (CI) values were calculated as previously described (21). The ToxiLight BioAssay Kit was purchased from Lonza Rockland, Inc.) and was used according to the manufacturer's instructions.

The RNAi screen comprised primary, secondary, and tertiary screens. The primary screen used single siRNAs targeting 84 candidate genes. Two-way ANOVA was used to classify positive hits as targets that induced a significant increase \((P < 0.05)\) in relative toxicity (cell death/cell viability), with either siRNA alone or siRNA combined with drug. This identified 30 positive hits that were carried forward to a secondary RNAi screen incorporating an additional 3 siRNA sequences per target. Positive hits were classified by a significant increase in relative toxicity with either siRNA alone or siRNA combined with drug for 2 or more of the additional siRNA sequences. This identified 11 positive hits that were carried forward to a tertiary RNAi screen. For each target, the optimum chemosensitizing siRNA from the primary and secondary RNAi screens was used in a panel of 6 independent CRC cell lines. siFGFR4_4 displayed particularly high levels of relative toxicity alone and was not considered. A positive hit was classified as a significant increase in relative toxicity with either siRNA alone or siRNA combined with drug in 3 or more CRC cell lines; this identified 6 positive hits.

**Q-PCR analysis**

siRNA silencing of the candidate genes was confirmed by Q-PCR, as described previously (15). Final expression values were normalized to GAPDH expression and presented relative to the untreated time-matched siRNA control (SC).

**Western blot analysis**

Western blots were carried out as previously described (22). Caspase-8 (12F5; Alexis) and poly-ADP-ribose-polymerase-1 (PARP; ebioscience) mouse monoclonal antibodies were used in conjunction with a horseradish peroxidase–conjugated sheep antimouse secondary antibody (Amersham). Caspase-3 rabbit polyclonal antibody (Cell Signaling Technology, Inc.) was used in conjunction with anti-rabbit secondary antibody (Amersham). GALR1 (Sigma) goat polyclonal antibody was used in conjunction with donkey anti-goat secondary antibody (Santa Cruz). Equal loading was assessed using GAPDH or actin (AbD Serotec).

**Annexin V/propidium iodide analysis**

Cells were harvested and analysed according to the manufacturer's instructions (BD Biosciences). Annexin V/propidium iodide (PI) analysis was carried out using the EPICS X1 Flow Cytometer (Coulter). Briefly, levels of apoptosis were calculated as the sum of FITC-Annexin V positive/PI negative (early apoptosis) and FITC-Annexin-V–positive/PI positive (late apoptosis) cell population.
Caspase activation assays
Caspase activity in cell protein isolates was measured using Caspase Glo 3/7, 8, and 9 assays (Promega).

Analysis of public CRC data sets
Association of target gene expression with CRC tumor.
Public CRC microarray data sets were accessed (23) and CRC tumor expression data for Galanin mRNA was downloaded (24, 25).

Association of target gene expression with clinical response.
Public CRC microarray data sets were accessed (26) and Galanin expression data sets GSE17536 (27), and GSE14333 (28) were downloaded. GraphPad Prism 5 software was used to generate a Kaplan–Meier survival curves for high- and low-expression groups. These were dichotomized at the optimal cutpoint, as calculated by log-rank test (26).

Results
Generation of in vitro and clinically derived genelists
An overview of our experimental approach is depicted in Fig. 1. Bioinformatic analysis of the 5-FU in vitro data identified 1,329 genes that were constitutively altered between the parental and resistant cell lines (Supplementary Table S1A), 1,389 genes that were 5-FU inducible in parental cells (Supplementary Table S1B), and 922 genes that were 5-FU–inducible in 5-FU–resistant cells (Supplementary Table S1C). For oxaliplatin, 1,164 genes were identified that were constitutively altered between the parental and resistant cell lines (Supplementary Table S1D), 643 genes that were oxaliplatin-inducible in parental cells (Supplementary Table S1E), and 373 genes that were oxaliplatin-inducible in oxaliplatin-resistant cells (Supplementary Table S1F). For oxaliplatin, 1,164 genes were identified that were constitutively altered between the parental and resistant cell lines (Supplementary Table S1D), 643 genes that were oxaliplatin-inducible in parental cells (Supplementary Table S1E), and 373 genes that were oxaliplatin-inducible in oxaliplatin-resistant cells (Supplementary Table S1F). For oxaliplatin, 1,164 genes were identified that were constitutively altered between the parental and resistant cell lines (Supplementary Table S1D), 643 genes that were oxaliplatin-inducible in parental cells (Supplementary Table S1E), and 373 genes that were oxaliplatin-inducible in oxaliplatin-resistant cells (Supplementary Table S1F).

Overlap between pathway analysis and GSEA
When the C2 and C5 GSEA results were compared with the pathway analysis results, apoptosis, calcium signalling, cell cycle, cell communication, cytokine–cytokine receptor interaction, focal adhesion/MAPK signalling, Gap junction, glycerophospholipid metabolism, insulin signaling, and regulation of actin cytoskeleton were found to significantly correlate with the GSEA (Fig. 1 and Table 1). From this list, we selected apoptosis, cell cycle, focal adhesion, MAPK signalling, and insulin signalling to study further.

Candidate gene selection
Candidate genes (n = 84) were chosen that passed a 1.5-fold change in expression with a P < 0.05 within the identified pathways, and nodal points within these pathways were prioritized (Supplementary Table S4). Ligands such as the fibroblast growth factors were identified within the MAPK signaling pathway; however, we opted to silence their receptors, to reduce the number of candidate genes to be screened.

Primary RNAi screen
To identify genes that when downregulated enhanced sensitivity to 5-FU/oxaliplatin, we used the HCT116 cell line for the primary RNAi screen and single siRNAs against 48 candidate genes. A positive hit was defined as a significant increase (P < 0.05) in relative toxicity (cell death/cell
Clinical samples: Pretreatment metastatic liver biopsies 4 Responders v 4 Nonresponders

Bioinformatic analysis: Genelist generation (Genespring v7.3.1)

Pathway analysis: KEGG and GenMAPP pathways (≥5 genes with 1.5 fold change, \( P < 0.05 \))

Gene Set Enrichment Analysis: Responders v Non-responders

5-FU: sensitive and resistant

Oxaliplatin: sensitive and resistant

HCT116 in vitro models:

Clinical biopsies

Transcriptional profiling:

Colorectal disease specific array (DSA)

Pathways

Gene sets

Apoptosis
Calcium signalling
Cell communication
Cell cycle
Cytokine–Cytokine receptor interaction
Focal adhesion
Gap junction
Glycerophospholipid metabolism
Insulin signalling
MAPK signalling
Regulation of actin cytoskeleton

RNAi screening

1. Primary (single siRNA/target, \( n = 84 \))
2. Secondary (3 siRNA/target, \( n = 30 \))
3. Tertiary (6 CRC cell lines, \( n = 11 \))

Novel chemo sensitizing targets (\( n = 6 \))

Figure 1. Experimental overview. Schematic of the systems biology approach used to identify novel determinants of resistance to 5-FU and oxaliplatin in CRC. Microarray profiling was carried out on sensitive and resistant in vitro models and clinical samples from responding and nonresponding patients. Genelists generated from the microarray data were analyzed by pathway analysis and gene set enrichment analysis was done to identify key pathways mediating resistance to 5-FU and oxaliplatin. Candidate genes from the selected pathways were functionally assessed by RNAi screening. CA, constitutively altered; IP, inducible parental; IR, inducible resistant; FDR, false discovery rate.
viability) with the targeting siRNA either alone or combined with chemotherapy, and this was determined by 2-way ANOVA. Thirty positive hits were identified in the primary RNAi screen: 15 MAPK targets, 8 focal adhesion targets (Fig. 2A), 3 cell-cycle targets, 2 insulin signaling targets, and 2 apoptosis targets (Supplementary Fig. S1A). The positive hits were carried forward to the secondary RNAi screen. A significant interaction ($P < 0.05$) between targeting siRNA and drug was observed for 11 of these genes (Supplementary Table S5A).

Secondary RNAi screen

To validate the primary screen "hits," 3 additional siRNAs per target were used, and sensitizing effects were determined as before. Multiple siRNAs reproduced a sensitizing phenotype for 11 of these targets: 6 MAPK targets (RAC2, RAPGEF2, FGFR4, MAPK9, GALR1, and TFDP1), 2 focal adhesion targets (EMP2 and FLNB; Fig. 2B), and 3 cell-cycle targets (CENPE, CDC20, and SMC4; Supplementary Fig. S1B). A significant chemotarget interaction was observed for siRNAs targeting RAC2, RAPGEF2, MAPK9, or GalR1 (Supplementary Table S5B). Gene silencing was confirmed by Q-PCR (Supplementary Fig. S2A and S2B).

Tertiary RNAi screen

The focus of further validation was based on the MAPK/focal adhesion targets identified in Fig. 2B. To rule out cell line-specific effects, a panel of 6 independent colorectal cancer cell lines (HCT116, LS174T, RKO, SW620, LoVo, and HT29) were incorporated into a tertiary RNAi screen. The optimum chemosensitizing siRNA for each target from the previous screens was used. Significant 5-FU/oxaliplatin sensitizing effects ($P < 0.05$) were determined as before. A sensitizing phenotype was observed across the cell line panel for 6 targets: GalR1 (Fig. 2C), MAPK9, RAC2, FGFR4, EMP2, and TFDP1 (Supplementary Fig. S1C). As a highly novel and potentially druggable target, the GalR1/galanin receptor–ligand axis was selected for further functional analyses.

GalR1/galanin silencing synergistically enhances the effects of chemotherapy

HCT116 cells were transfected for 24 hours with GalR1 siRNA (siGALR1) or galanin siRNA (siGAL) before a 24-hour/48-hour cotreatment with IC$_{50}$ drugs of 5-FU/oxaliplatin. GalR1 silencing was confirmed by Western blot (Fig. 3A, inset) and galanin silencing was confirmed

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<th>5-FU in vitro</th>
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NOTE: Pathways identified by pathway analysis contained 5 or more genes with a 1.5-fold change and $P < 0.05$. Only pathways identified from 4 or more genelists are listed.

Table 1. Pathways common to gene set enrichment analysis (GSEA) of the clinical genelist and pathway analysis of in vitro and clinical genelists
by Q-PCR (Fig. 3B, inset). Cell viability was determined by MTT assay, and CI values were calculated (Fig. 3A). These analyses showed that siGALR1 was synergistic with 5-FU and oxaliplatin treatment, particularly at lower concentrations of siRNA. Furthermore, synergy was also observed between siGAL and chemotherapy treatment (Fig. 3B). Synergy was also showed in the RKO and LS174T cell lines after GalR1 silencing or galanin silencing (Supplementary Fig. S3A and data not shown) and the H630 cell line after galanin silencing (data not shown).

Figure 2. Positive hits from RNAi screening. A, the primary RNAi screen was carried out in the HCT116 cell line with 1 siRNA sequence per target to functionally assess 84 candidate genes from key pathways. A positive hit was defined by 2-way ANOVA as a significant ($P < 0.05$) increase in relative toxicity (cell death/cell viability) with siRNA alone or siRNA combined with drug. B, a secondary RNAi screen used an additional 3 siRNA sequences per target. A positive hit was classified as a significant increase in relative toxicity alone or combined with drug in $\geq 2$ additional siRNA sequences. C, a tertiary RNAi screen used the optimum chemosensitizing siRNA from the previous screens and incorporated a panel of 6 independent CRC cell lines. A positive hit was classified as a significant increase in relative toxicity alone or combined with drug in $\geq 3$ cell lines. Results are given as mean values $\pm$ SEM of triplicate measurements. *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$. SC, siRNA control; si, targeted siRNA; SOL, solvent control.
Figure 3. Galanin/GalR1 silencing is synergistic with chemotherapy treatment. Cell viability assays were conducted in the HCT116 parental cell line and the Chou and Talalay method was used to evaluate the interaction between GalR1 siRNA (siGALR1; A) or galanin siRNA (siGAL; B) and increasing concentrations of either 5-FU or oxaliplatin at 48/72 hours. CI values $<1$, $1$, and $>1$ indicating synergism, additivity, and antagonism, respectively. GALR1 silencing was confirmed by Western blot (A, inset) and galanin silencing was confirmed by Q-PCR (B, inset). C, cell viability of HCT116 oxaliplatin-resistant (OXR) and 5-FU-resistant (FUR) cell lines after galanin/GalR1 silencing (10 nmol/L siRNA) for 24 hours before 48-hour cotreatment with parental IC30(48 h) and IC50(48 h) doses of chemotherapy. A synergistic interaction was determined by 2-way ANOVA.

D, Annexin V/PI flow cytometric analysis was used to measure apoptosis levels in HCT116 parental cells after galanin/GalR1 silencing (5 nmol/L siRNA) for 24 hours before a 24-hour cotreatment with IC30(48 h) doses of either 5-FU or oxaliplatin. D (inset), Western blot showing PARP cleavage in HCT116 cells transfected with 5 nmol/L siGALR1 for 24 hours before a 24-hour cotreatment with approximately IC30(48 h) doses of either 5-FU or oxaliplatin. Results are given as mean values ± SEM of triplicate measurements. *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$. SC, siRNA control.
Figure 4. Galanin/GalR1 silencing induces caspase-8-dependent apoptotic cell death. Annexin V/PI flow cytometric analysis was used to measure apoptosis levels. A, HCT116 cells were transfected with 5 nmol/L siGALR1 and 10 μmol/L zVAD for 24 hours before a 24-hour cotreatment with IC_{50} doses of either 5-FU or oxaliplatin. B, caspase-3/7 and 8 activity levels in HCT116 cells after 24 hours GalR1 silencing (5 nmol/L siRNA) before a 24-hour cotreatment with IC_{50} doses of either 5-FU or oxaliplatin. C, HCT116 cells after 48 hours GalR1/galanin (5 nmol/L siRNA) and caspase-8 (10 nmol/L siRNA) cosilencing. C (inset), Western blotting was used to measure expression of PARP, caspase-8, and FLIPL after 24 hours GalR1 and caspase-8 cosilencing. D, HCT116 parental cells and the FLIPL overexpressing cell line, FL17, after 24 hours GalR1/galanin silencing (5 nmol/L siRNA). Results are mean values ± SEM of triplicate measurements. *, P < 0.05; **, P < 0.01; ***, P < 0.001; SC, siRNA control.
Drug-resistant HCT116 models were also transfected for 24 hours with siGALR1 or siGAL before 48-hour cotreatment with parental IC_{50(48 h)} and IC_{50(48 h)} doses of 5-FU/oxaliplatin. A significant reduction in cell viability was observed after GalR1 or galanin silencing alone in both the oxaliplatin- and 5-FU–resistant HCT116 models, and this was further reduced when combined with chemotherapy treatment (Fig. 3C). This reduction in viability was synergistic for siGAL and oxaliplatin treatment. A similar interaction was observed in the oxaliplatin-resistant HCT116 p53 null model (Supplementary Fig. S3B). Silencing of galanin alone but not GalR1 significantly reduced cell viability in other 5-FU–resistant models (LoVo and HT29; Supplementary Fig. S3C). Of note, galanin/GalR1 silencing also significantly reduced cell viability in models (HCT116, LoVo, and HT29) resistant to the active metabolite of irinotecan, the other chemotherapeutic agent currently approved for use in advanced CRC (Supplementary Fig. S3D). These results indicate that drug-resistant models maintain the dependency on galanin signaling observed in the parental drug-sensitive cell lines.

**GalR1/galanin silencing induces apoptosis in CRC cell lines**

To determine the mechanism of chemosensitization after silencing of GalR1 and galanin, HCT116 cells were transfected with 5 nmol/L siGALR1 or siGAL for 24 hours before a 24-hour cotreatment with approximately IC_{50(48 h)} doses of 5-FU or oxaliplatin; apoptosis levels were determined by flow cytometry. GalR1 silencing for 48 hours resulted in significantly higher levels of apoptosis (~47%) compared with ~10% in the control siRNA (SC) transfected cells (P < 0.001; Fig. 3D). This was further enhanced to ~59% when combined with 5-FU and approximately 69% when combined with oxaliplatin; 2-way ANOVA confirmed a significant interaction between siGALR1 and 5-FU/oxaliplatin (P < 0.001). Similar results were observed after galanin silencing (Fig. 3D) and Western blot analysis showed PARP cleavage (a hallmark of apoptosis) after GalR1 silencing (Fig. 3D, inset), supporting the flow cytometry results. This chemosensitizing phenotype was reproduced using a second siRNA sequence for both GalR1 (siGALR1_1) and galanin (siGAL; Supplementary Fig. S4A). To assess whether the effects were cell line-specific, LS174T and RKO CRC cell lines were analyzed (Supplementary Fig. S4B). In these models, the effect of GalR1/galanin silencing on induction of apoptosis was less than in the HCT116 cells. However, the sensitization to chemotherapy-induced apoptosis was still observed in both these models and was again particularly marked for oxaliplatin. A significant induction of apoptosis was observed after GalR1 or galanin silencing alone in drug-resistant models (Supplementary Fig. S4C) and Western blot analysis showed PARP cleavage and activation of the executioner caspase, caspase-3 after GalR1/galanin silencing, further supporting the flow cytometry results (Supplementary Fig. S4D).

**GalR1/galanin silencing downregulates FLIP\_L and activates caspase-8-dependent apoptosis**

Caspase-dependent apoptosis after GALR1 silencing was confirmed using the pan-caspase inhibitor, zVAD, which completely attenuated apoptosis (Fig. 4A). Analysis of caspase activity after GalR1 silencing indicated that there was a close correlation between the activity of the executioner caspases-3 and -7 and the initiator caspase, caspase-8 (Pearson correlation coefficient r = 0.99), suggesting a role for caspase-8 in initiation of the apoptotic phenotype (Fig. 4B). To investigate this further, HCT116 cells were cotransfected with siGALR1 and siCasparse 8 for 48 hours. Notably, cosilencing of caspase-8 resulted in inhibition of siGALR1-induced apoptosis (Fig. 4C). Western blot analysis showed that GalR1 silencing induced PARP cleavage and processing of procaspase 8 and that PARP cleavage was blocked by cosilencing of caspase-8 (Fig. 4C, inset). Similarly, the apoptosis induced by galanin silencing (Fig. 4C and Supplementary S5A) was blocked by cotransfection with siCasparse 8 (Fig. 4C).

Given the caspase-8–dependent manner of siGALR1/siGAL-induced apoptosis, the expression of FLIP\_L, an endogenous inhibitor of caspase-8 activation, was investigated. FLIP\_L levels were found to be downregulated after transfection with siGALR1 (Fig. 4C, inset and Supplementary Fig. S5B) or siGAL (Supplementary Fig. S5A). FLIP\_L downregulation was confirmed with 2 additional siRNA sequences (ref. 29; siGALR1_1 and siGALR1_4; Supplementary Fig. S5C) and an additional CRC cell line (RKO; Supplementary Fig. S5D). Moreover, a FLIP\_L overexpressing cell line FL17 (17) was significantly resistant to apoptosis induction after GalR1/galanin silencing compared with the parental HCT116 cell line (P < 0.01; Fig. 4D). These results indicate for the first time that FLIP\_L is a key downstream effector of GalR1/galanin-mediated anti-apoptotic signaling.

**Clinical relevance of galanin expression in CRC**

Using publicly available data sets, galanin mRNA expression was found to be significantly upregulated in CRC tumors compared with normal colon from 2 independent studies: a 1.7-fold increase; \( P = 3.2E^{-5} \) (Fig. 5A; refs. 23 and 24) and a 1.9-fold increase; \( P = 2.59E^{-8} \) (Fig. 5B; refs. 23 and 25).

Having identified galanin and its receptor as determinants of chemotherapy resistance, we examined whether galanin mRNA expression was a potentially useful clinical biomarker in CRC. Using the oxaliplatin constitutively altered (CA) genelist (Supplementary Table S1D), GSEA identified genes that were enriched and upregulated in nonresponding patients (FDR < 25%). Galanin was identified in the top 24 genes that were significantly upregulated (P < 0.05) and enriched in both the oxaliplatin-resistant cells and nonresponding patients (Supplementary Table S3C). We then examined the prognostic value of galanin mRNA expression, because predictive biomarkers may also have prognostic value. Importantly, analysis of galanin mRNA expression in the early stage
patients within the GSE17536 CRC data set (27) revealed a significant correlation between high galanin expression and decreased disease-free survival (DFS; Fig. 5C; \( P = 0.0077; n = 135 \)). Notably, when the early stage patient cohort was broken down into individual stages, this correlation was lost in the stage III cohort, but remained highly significant in the stages I and II cohorts (Fig. 5C; \( P = 0.0036 \) and \( P = 0.0025 \), respectively). In a separate CRC data set (GSE14333; ref. 28), a significant correlation between high galanin mRNA expression and poorer disease-free survival was also observed in the Dukes stage B (stage II) patients (Fig. 5D; \( P = 0.03 \)). Nonsignificant trends were observed between high galanin mRNA expression and poorer DFS in Dukes A disease (stage I; \( P = 0.06 \)) and when stages A, B, and C were combined (\( P = 0.098 \)). This data suggests a potential association between high galanin mRNA expression and poor patient outcome in early stage CRC. There were insufficient numbers of clinical samples within these public data sets to explore the potential of galanin as a predictive biomarker; ongoing studies aim to further examine the clinical relevance of galanin mRNA expression as both a predictive and prognostic factor.
Resistance to chemotherapy remains a major problem in CRC, both in the adjuvant and advanced disease settings. In this study, we used a systems biology approach comprising both in vitro and clinical microarray data to identify novel genes and pathways that regulate 5-FU/oxaliplatin resistance together with a functional genetic approach to identify chemosensitizing interactions between specific proteins and chemotherapy in CRC cells. Pathway analysis and GSEA identified MAPK signaling, insulin signaling, cell cycle, focal adhesion, and apoptosis as key determinants of drug sensitivity. Using an siRNA screening approach, we examined whether downregulating specific nodal points within these pathways enhanced 5-FU/oxaliplatin sensitivity. From the chemosensitizing targets identified in our study, GalR1 was considered to be highly novel and was prioritized for further functional analysis.

GalR1 is one of 3 galanin receptors and is the predominantly expressed galanin receptor in the human colon (30). The galanin receptor ligands are neuropeptides and include galanin (GAL), galanin-message–associated peptide (GMAP), a derivative from the same peptide precursor as galanin, galanin-like peptide (GALP), which is encoded by a different gene, and alarin, which is encoded by a splice variant of the GALP gene. Galanin's functions in the GI tract include inhibition of gastric acid secretion and inhibition of the release of pancreatic peptides such as insulin, amylase, glucagons, and somatostatin. This study focused on GalR1 and the ligand, galanin, as to date, no specific GI tract functions have been delineated for GalR2, GalR3, or the ligands GMAP, GALP, or alarin (30).

There are many reports of cancer-promoting properties for GalR1. It is known to signal through the MAPK pathway, and mitogenic effects of galanin have been reported in pancreatic cancer cells (31), small cell lung cancer cells (32) and rat pituitary tumor cells in vitro (33). Galanin has also been found to be upregulated in the serum of CRC patients compared with healthy donors (34), and CGH analyses showed gains at the galanin locus, 11q13, in CRC metastases (35), which has been associated with poor outcome (36). In contrast, GalR1 has been implicated as a tumor suppressor because loss of the GALR1 locus, 18q23, have been reported in HNSCC (37) and metastatic CRC tumors (30, 38). In addition, galanin stimulation of GalR1 overexpressing oral SCCs was shown to induce ERK activation, and this was associated with suppressed cell proliferation, inhibition of colony formation, and suppressed tumor growth in vivo (39). It has been suggested that the different signal transduction pathways associated with each galanin receptor may account for distinct biological

Figure 5. (Continued) CRC GSE14333 data set (probe ID: 214240_at; D) revealed a trend for high galanin and decreased disease-free survival in combined stages ($P = 0.098; n = 246$) and Duke’s A patients ($P = 0.06$). There was a significant correlation between high galanin expression and decreased disease free survival in the Duke’s B patients ($P = 0.03$).
activities of galanin in different types and possibly different stages of cancer (30). Therefore, the impact of galanin signaling may depend on the expression level of each receptor, which in turn may vary in a tissue and tumor-specific manner. Galanin is considered to be a marker of pluripotent stem cells. Four of the most significantly overexpressed genes in undifferentiated embryonic tissue are galanin, Pou5f1 (Oct3), Nanog, and Dppa4 (10, 12) with galanin highlighted as the most abundantly expressed in human and rodent embryonic stem cells (10, 14). Furthermore, a 92 gene molecular signature of "stemness" in 6 human ESC lines found that galanin mRNA was the most abundant transcript, along with those of Pou5f1, Nanog, Sox2, and FoxD3 (9, 10). Upregulation of galanin mRNA and protein expression has been reported in undifferentiated embryonal carcinoma, suggesting it may be a diagnostic marker for undifferentiated tumor cells (40). Cancer cells possessing stem-cell properties have been described in solid tumors, and it is hypothesized that tumor cells with stem-cell attributes are chemo-refractory (41, 42). It is possible therefore that galanin’s potential role in maintaining stem-cell-like properties is linked to the novel role we have identified for this ligand in mediating chemotherapy resistance in CRC. Further work is ongoing to explore this possibility.

Analysis of our microarray data sets using a customized GSEA found that high galanin mRNA expression was enriched in the oxaliplatin-resistant setting in vitro and in non-responding patients. Further investigation of galanin mRNA expression in public data sets revealed that galanin was overexpressed in colorectal tumors compared with normal colon. Importantly, high galanin expression was also significantly associated with poorer DFS of CRC patients, specifically in early stage disease. The clinical management of stage II CRC is a matter of debate as the majority of patients are cured by surgery alone (43). The identification of the 15% to 20% of stage II CRC patients who are most likely to relapse is therefore highly clinically relevant as these patients could be selected for treatment with adjuvant chemotherapy, whereas the patients who are unlikely to relapse could be spared the toxic side effects of chemotherapy treatment. A number of studies, including one involving our group, have attempted to identify prognostic biomarkers for stage II CRC (44–46). The preliminary data presented in this study suggest that galanin mRNA expression may be a useful prognostic biomarker for stage II disease; this is currently being examined in larger patient cohorts.

Previous findings by our group have identified FLIP, in particular FLIPⅠ, as a key determinant of drug resistance in CRC (3). The mechanism by which GalR1 silencing enhanced chemosensitivity in CRC was shown to involve caspase-8–dependent apoptosis after downregulation of FLIPⅠ. This is the first demonstration of a link between FLIP and galanin/GalR1; the mechanistic basis by which GalR1/galanin regulates the expression of FLIP and other downstream apoptosis-regulating proteins is the subject of ongoing studies. We previously found that high FLIP expression was an independent prognostic factor in stage II/III CRC (47). Given the prognostic significance of galanin expression and its role as an upstream regulator of FLIP expression, it is possible that high galanin levels promote high FLIP expression in CRC tissues resulting in a more aggressive disease phenotype. This would implicate the galanin signaling pathway as a potentially important therapeutic target in CRC.

In summary, using a systems biology approach, we have identified several pathways as potential mediators of 5-FU/oxaliplatin response and resistance. From these analyses, we identified GalR1/galanin as a novel receptor ligand system that regulates CRC cell survival and drug resistance. The mechanism by which GalR1/galanin mediates 5-FU/oxaliplatin resistance in CRC was found to be due (at least in part) to its upstream regulation of FLIPⅠ expression. Notably, galanin mRNA expression was found to be upregulated in colorectal tumor versus normal tissue and overexpressed and enriched in the non-responding patients of this study. Moreover, high galanin mRNA levels also correlated with a poorer prognosis in CRC patient cohorts, particularly in stage II disease. Together, these findings provide the foundation for further research into GalR1/galanin as a novel therapeutic target and/or prognostic biomarker in CRC.

Disclosure of Potential Conflicts of Interest
P.G. Johnston is employed by and has an ownership interest in Almac Diagnostics and Fusion Antibodies. He has received a research grant from Invitrogen/McClay Foundation/QB. He is a consultant/advisor for Chugai pharmaceuticals, Sanofi-Aventis and on the board of the Society for Translational Oncology. He has honoraria from Chugai Pharmaceuticals, Sanofi-Aventis, and Precision therapeutics.

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