Association of MGMT Promoter Methylation Status With Survival Outcomes in Patients With High-Risk Glioma Treated With Radiotherapy and Temozolomide: An Analysis From the NRG Oncology/RTOG 0424 Trial

Erica H. Bell
Peixin Zhang
Barbara J. Fisher
David R. Macdonald
Joseph P. McElroy

See next page for additional authors

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**IMPORTANCE** The initial report of NRG Oncology/Radiation Therapy Oncology Group (RTOG) 0424 demonstrated a 3-year overall survival benefit with the addition of temozolomide to radiotherapy compared with a historical control. However, an important end point of the trial—evaluation of the association between O6-methylgaunine-DNA-methyltransferase (MGMT) promoter methylation and survival outcomes—was not previously reported.

**OBJECTIVE** To examine the proportion of patients in NRG Oncology/RTOG 0424 with MGMT promoter methylation and its association with survival outcomes.

**DESIGN, SETTING, AND PARTICIPANTS** Specimens collected were analyzed after trial completion to determine MGMT promoter methylation and IDH1/2 status and the association between MGMT status and survival outcomes. A model derived from logistic regression (MGMT-STP27) was used to calculate MGMT promoter methylation status. Univariate and multivariable analyses were performed using the Cox proportional hazards regression model to determine the association of MGMT status with survival outcomes. Patient pretreatment characteristics were included as covariates in multivariable analyses.

**MAIN OUTCOMES AND MEASURES** Progression-free survival (PFS) and overall survival (OS).

**RESULTS** Of all 129 eligible patients in NRG Oncology/RTOG 0424, 75 (58.1%) had MGMT status available (median age, 48 years; age range, 20-76 years; 42 [56.0%] male): 57 (76.0%) methylated and 18 (24.0%) unmethylated. A total of 13 unmethylated patients (72.2%) had astrocytoma as opposed to oligoastrocytoma or oligodendroglioma, whereas 23 methylated patients (40.4%) had astrocytoma. On univariate analyses, an unmethylated MGMT promoter was significantly associated with worse OS (hazard ratio [HR], 3.52; 95% CI, 1.64-7.56; \( P < .001 \)) and PFS (HR, 3.06; 95% CI, 1.55-6.04; \( P < .001 \)). The statistical significances were maintained in multimarker multivariable analyses, including IDH1/2 status for both OS (HR, 2.70; 95% CI, 1.02-7.14; \( P = .045 \)) and PFS (HR, 2.74; 95% CI, 1.19-6.33; \( P = .02 \)).

**CONCLUSIONS AND RELEVANCE** In this study, MGMT promoter methylation was an independent prognostic biomarker of high-risk, low-grade glioma treated with temozolomide and radiotherapy. This is the first study, to our knowledge, to validate the prognostic importance of MGMT promoter methylation in patients with grade II glioma treated with combined radiotherapy and temozolomide and highlights its potential prognostic value beyond IDH1/2 mutation status.

**TRIAL REGISTRATION** ClinicalTrials.gov Identifier: NCT00114140
low-grade gliomas (LGGs; World Health Organization [WHO] grade II) display significant variability in clinical behavior. Median survival times range from a few to more than 10 years. Accordingly, optimal management remains controversial. The role of chemotherapy had not been established until the recent results of NRG Oncology/Radiation Therapy Oncology Group (RTOG) 9802, which revealed improved overall survival (OS) among patients with high-risk LGG treated with radiotherapy and a procarbazine, lomustine, and vincristine (PCV) regimen compared with radiotherapy alone. However, significant adverse effect profiles of PCV often prevent patients from completing planned therapy. Therefore, use of temozolomide, a more tolerable alkylating agent, instead of PCV in LGG is currently under active investigation.

NRG Oncology/RTOG 0424 was a single-arm, phase 2 study of high-risk LGG treated with radiotherapy and temozolomide and represents the only completed trial of radiotherapy plus temozolomide in LGGs. High risk was defined as having at least 3 of 5 risk factors as defined by Pignatti et al: age older than 40 years, largest preoperative tumor diameter of 6 cm or more, tumor invading the corpus callosum, astrocytoma histologic features, and preoperative neurologic deficits. The initial report of this study showed a 3-year OS rate of 73.1% among those treated with temozolomide-based chemoradiotherapy, which was significantly higher than the rate in a historical control group of 54% for treatment with radiotherapy alone. However, the analyses of O6-methylguanine-DNA-methyltransferase (MGMT) (OMIM 156569) methylation were not available in the initial report. The protocol was amended during accrual to mandate tissue sample submission for retrospective analysis of MGMT status because the importance of MGMT was not known at the time of trial design. Promoter methylation of MGMT results in epigenetic silencing of the MGMT gene and associated loss of protein expression, leading to accumulation of DNA damage and increased sensitivity to temozolomide. Previous clinical studies have found a prognostic effect of MGMT promoter methylation in patients with glioblastoma treated with temozolomide-based chemoradiotherapy. Thus, analysis of MGMT promoter methylation is essential to further evaluate the added benefit of temozolomide to radiotherapy in patients with LGG.

Correlative data from LGG phase 3 trials are limited because of tumor rarity and related tissue collection and follow-up requirements. Only a recent phase 3 study (European Organisation for Research and Treatment of Cancer trial 22033-2603) of grade II gliomas, which randomized patients to receive radiotherapy or temozolomide, has analyzed MGMT status in prospectively treated patients with grade II gliomas. MGMT status was found to be methylated in 135 of the 150 tumors tested (90.0%). To date, no significant progression-free survival (PFS) difference has been detected in patients treated with radiotherapy or temozolomide in this study; OS analyses and full evaluation of the predictive potential of molecular subtypes have not yet been completed.

Of importance, NRG Oncology/RTOG 0424 is the only LGG trial using a temozolomide-based chemoradiotherapy regimen, providing a unique opportunity to evaluate molecular markers. This follow-up study to the initial report sought to evaluate MGMT methylation status and its association with survival outcomes in conjunction with isocitrate dehydrogenase 1 (IDH1) (OMIM 147700) or isocitrate dehydrogenase 2 (IDH2) (OMIM 147650) mutational status because of their known association with the hypermethylation (glioma-CpG island methylator phenotype) phenotype. We report, for the first time to our knowledge, the proportion of MGMT methylation and its prognostic significance (a study end point) in a prospective study of radiotherapy and temozolomide in high-risk LGG (NRG Oncology/RTOG 0424).

Methods

Collected specimens were analyzed to determine MGMT promoter methylation (a prespecified secondary end point of the study) and IDH1/2 status (a post hoc analysis) and correlation between MGMT status and survival outcomes. A model derived from logistic regression (MGMT-TP27) was used to calculate MGMT promoter methylation status from Illumina HumanMethylation450 BeadChip data. IDH1/2 mutation status was determined by next-generation sequencing with a customized IonTorrent panel. The OS was defined as time from registration to death or the last follow-up date on which patients were reported to be alive. The PFS was defined as time from registration to progression or death, whichever came first, or the last follow-up date on which patients were reported to be alive without disease progression. The OS and PFS rates were estimated using the Kaplan-Meier method. Hazard ratios (HRs) were calculated using the Cox proportional hazards regression model and tested using the log-rank test. Multivariable analyses were performed, including age, sex, histologic features, neurologic function, Zubrod performance score, and tumor crossing midline as covariates. Patients participating in NRG Oncology/RTOG 0424 provided informed consent based on an institutional review board–approved protocol at the enrollment site. The correlative analysis was conducted with an institutional review board–approved waiver of consent from The Ohio State University because of the retrospective and deidentified nature of the study.
Results

Of all 129 eligible patients, 75 (58.1%) had MGMT status available (median age, 48 years; age range, 20-76 years; 42 [56.0%] male) (Figure 1). Most of the patient pretreatment characteristics were comparable between patients with and without MGMT status (eTable 1 and eTable 2 in the Supplement). Because of limited biopsy tissue, it is understandable that most patients with MGMT status underwent partial or total resection (eTable 1 and eTable 2 in the Supplement). As expected, most unmethylated patients (13 [72.2%]) had astrocytoma as opposed to oligodendroglioma or mixed tumors, whereas 23 methylated patients (40.4%) had astrocytoma (eTable 1 in the Supplement). Of the 75 patients, 57 (76.0%) were methylated patients (40.4%) had astrocytoma (Figure 1). No patients were lost to follow-up. On univariate analyses, an unmethylated MGMT promoter was significantly associated with worse OS (hazard ratio [HR], 3.52; 95% CI, 1.64-7.56; P < .001) and PFS (HR, 3.06; 95% CI, 1.55-6.04; P < .001) (Figure 2). The median OS and PFS times were not reached for the methylated group but were 3.0 years for OS (95% CI, 2.3 to not reached) and 2.0 years (95% CI, 0.9-4.9 years) for PFS for the unmethylated group (Figure 2). On multivariable analyses, without including IDH1/2 mutation status, statistical significances were maintained, with an HR of 2.89 (95% CI, 1.31-6.38; P = .009) for OS and an HR of 2.97 (95% CI, 1.48-5.96; P = .002) for PFS (Table). Because of the association between MGMT promoter methylation and IDH1/2 mutation status, multimarker multivariable analyses were also performed (Table), and statistical significances for the effects of MGMT promoter methylation were maintained for both OS (HR, 2.70; 95% CI, 1.02-7.14; P = .045) and PFS (HR, 2.74; 95% CI 1.19-6.33; P = .02).

Discussion

Although the results from the primary analyses of NRG Oncology/RTOG 0424 demonstrated a benefit with the addition of temozolomide to radiotherapy compared with the historical control, there are multiple limitations to consider. The molecular landscape of the patients in this study and in the historical control data was unknown. Consequently, the current study regarding MGMT methylation status is critical because the trial could potentially be unrepresentative of the whole patient population with respect to MGMT methylation or the newly defined WHO molecular subgroups.15

Of importance, the current study on a subset of patients found that most patients were MGMT methylated. For the first time to our knowledge, this study showed in prospectively collected grade II tumors treated with radiotherapy plus temozolomide that MGMT promoter methylation was significantly associated with PFS and OS, in consideration of other important clinical variables and IDH1/2 mutations. The results are critical, demonstrating that MGMT methylation may be a prognostic biomarker and may represent a class of patients who have better prognoses.
Table. Cox Proportional Hazards Regression Model for Overall and Progression-Free Survivala

<table>
<thead>
<tr>
<th>Survival</th>
<th>Hazard Ratio (95% CI)</th>
<th>P Value</th>
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<tr>
<td>Overall survival</td>
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<tr>
<td>Unimarker analysis</td>
<td></td>
<td></td>
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<tr>
<td>MGMT status (unmethylated vs methylated)</td>
<td>2.89 (1.31-6.38)</td>
<td>.009</td>
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<tr>
<td>Age (continuous)</td>
<td>1.06 (1.02-1.10)</td>
<td>.007</td>
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<tr>
<td>Multimarker analysisb</td>
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<tr>
<td>MGMT status (unmethylated vs methylated)</td>
<td>2.70 (1.02-7.14)</td>
<td>.045</td>
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<tr>
<td>IDH1/2 status (mutant vs nonmutant)</td>
<td>0.42 (0.16-1.12)</td>
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<td>Age (continuous)</td>
<td>1.05 (1.00-1.10)</td>
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<tr>
<td>Progression-free survival</td>
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<tr>
<td>MGMT status (unmethylated vs methylated)</td>
<td>2.97 (1.48-5.96)</td>
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<tr>
<td>Sex (male vs female)</td>
<td>2.91 (1.35-6.29)</td>
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<td>Multimarker analysisb</td>
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<tr>
<td>MGMT status (unmethylated vs methylated)</td>
<td>2.74 (1.19-6.33)</td>
<td>.02</td>
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<tr>
<td>IDH1/2 status (mutant vs nonmutant)</td>
<td>0.51 (0.22-1.15)</td>
<td>.10</td>
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<tr>
<td>Sex (female vs male)</td>
<td>0.32 (0.14-0.72)</td>
<td>.006</td>
</tr>
</tbody>
</table>

a All models derived from stepwise selection with a significant level of .10 for entering into the model. Variables considered in all models were as follows: MGMT promoter methylation status, age, sex, histologic features, neurologic function, Zubrod score, and tumor crossing the midline. Most patients had partial or total resection; therefore, the extent of surgery (biopsy vs resection) was not included as a covariate in this analysis. Most patients had the largest preoperative tumor diameter of 5 cm or greater; therefore, tumor size (<5 vs ≥5 cm) was not included as a covariate in this analysis.

b Multimarker analysis was performed using 67 patients for which both IDH mutation status and MGMT methylation status were available.

Limitations
Because of the limitations of the small sample size of the entire study and specifically the IDH nonmutant population, it will be important to delineate in the future whether MGMT promoter methylation adds prognostic value only to the IDH nonmutant subgroup (eFigure 1 and eFigure 2 in the Supplement). Another limitation of this study is that molecular data were not available from historical controls. Therefore, we could not fully determine from the current data which molecular subtypes of LGGs benefit from the addition of temozolomide to radiotherapy. Thus, it is imperative that future clinical trials include molecular markers as stratification or eligibility criteria. Future analyses will include examining the prognostic significance of MGMT methylation with other known prognostic markers, such as the newly defined WHO subgroups (including 1p/19q codeletion status) with long-term follow-up data.

Conclusions
This study demonstrated that MGMT methylation may be an independent prognostic biomarker of high-risk LGGs treated with temozolomide and radiotherapy in NRG Oncology/ RTOG 0424. Which LGG molecular subtypes receive benefit from the addition of temozolomide to radiotherapy remains elusive. Of note, this is the first study, to our knowledge, to validate the prognostic importance of MGMT promoter methylation in patients with LGGs treated with temozolomide and radiotherapy by using multivariable analyses with prospectively collected clinical data.

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Author Affiliations: Department of Radiation Oncology, The Ohio State University, Columbus (Bell, Fleming, Chakraborty, Liu, Becker, Fabian, Chakravarti); Statistics and Data Management Center, NRG Oncology, Philadelphia, Pennsylvania (Zhang); Department of Radiation Oncology, London Regional Cancer Program, London, Ontario, Canada (Dhawan); Department of Radiation Oncology, H. Lee Moffitt Cancer Center & Research Institute, Tampa, Florida (Yu); Department of Radiation Oncology, Mayo Clinic, Rochester, Minnesota (Laack); Department of Radiation Oncology, Medical College of Wisconsin, Milwaukee (Schultz); Department of Obstetrics and Gynecology, University of Washington Medical Center–Accruals University of California San Francisco, Seattle (Gray); Departments of Medicine, Human Oncology and Neurology, University of Wisconsin Hospital, Madison (Robins); Department of Radiation Oncology, Baptist Hospital of Miami, Miami, Florida (Mehta).


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