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Evan J. Bian April 2nd, 2025

Single-System Study of Variations in BT-RADS Score Distributions for MRIs of Brain Tumors Based on Patient and Reader Characteristics

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Abstract

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Importance: The radiology report can have significant variation dependent on subjective radiologist preference, leaving the door open for ambiguity and inconsistency. This is problematic for accurately assessing clinical outcomes in brain tumor patients through MRI, where it can already be challenging to differentiate progression from treatment-related changes. A Brain Tumor Reporting and Data System (BT-RADS) was introduced to provide neuroradiologists with a structured reporting method, but its performance in clinical use and variation between different physicians is not completely understood

Objective: To understand how the distribution of BT-RADS scores varies between individual physicians, tumor types, and tumor mutational burden in actual usage at a healthcare system.

Methods: 4246 consecutive MRI scans of brain tumors for 928 unique patients between Jan. 2021 and Sept. 2024 across Emory Healthcare were analyzed. Only faculty members who read over 100 scans were included. Data was collected on tumor type, IDH mutation, and MGMT methylation.

Results: Out of 96 inter-reader comparisons for BT-RADS scoring rates, 80.2% exhibited no significant difference between physicians and the overall score distribution. Significant differences were observed when comparing distributions based on common tumor types as well as between different genetic backgrounds.

Conclusion: BT-RADS demonstrated strong usage similarities by independent radiologists across a single healthcare system. Furthermore, the system encompasses information that can capture how unique tumor characteristics such as type and mutational burden can dictate patient prognosis and outcomes. The reporting system shows promise as an effective standardized system to communicate information on brain tumor MRIs.

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Table of Contents

INTRODUCTION

The brain tumor is a rare disease affecting approximately 48 out of 100,000 individuals each year in the United States [1]. Despite numerous advances in research and therapies, these cancers remain a complex and challenging diagnosis to care for, often requiring a large interdisciplinary team to manage surgical and medical treatments [2]. Common treatment options of brain tumors include surgical resection by neurosurgical teams, radiotherapy directed by radiation-oncologists, and chemotherapy prescribed by neuro-oncologists. Even with comprehensive care, brain tumor prognosis remains poor with median survival times for the most aggressive tumors being just around a year, while less aggressive tumors give patients only 2-5 years [3].

The most common type of malignant brain tumor is the glioma, a tumor which arises from the support cells of the brain. Gliomas include astrocytomas, oligodendrogliomas, ependymomas, and other rare histologies which are differentiated by their unique molecular and genetic profiles. Other common tumor types are metastases, tumors that have migrated to the brain, often from lung or breast cancers. The final of the three most common brain tumor types are meningiomas, which are mostly slow-growing and benign, and generally have favorable prognoses.

In addition to the different types of brain tumors, genetic mutations and molecular markers can affect the treatment decisions made by care teams as well as affect the patient's survival rate [4]. Common mutations such as isocitrate dehydrogenase 1 (IDH1) or 1p/19q chromosomal deletions affect the cancer's ability to resist chemotherapies, and care teams often opt for chemotherapy (such as PCV, temozolomide, or others) alongside radiotherapy to give patients a survival advantage [5, 6]. Another very common molecular marker is the O-6-

methylguanine-DNA methyltransferase (MGMT) methylation, of which detection can indicate to care teams that the tumor may have decreased resistance to chemotherapy [7].

While brain tumors may have a multitude of factors influencing their severity, their diagnostic process often begins with imaging, such as a magnetic resonance imaging (MRI) scan, to confirm a tumors presence [8, 9]. Imaging can be highly suggestive of tumor, but biopsy is needed to confirm the diagnosis and determine the specific characteristics of the tumor. During diagnosis and treatment, the MRI scan is a straightforward process which can allow clinicians to view the tumor and monitor it longitudinally in a non-invasive fashion. However, it is critical that information from the MRI is accurately conveyed between radiologists and other providers.

A radiology report is the primary method of communication between radiologist and clinician, but there is currently no standardized way to report on brain tumors. As a result, the free-prose radiology report can have vast stylistic variation dependent on radiologist preference, leaving the door open for ambiguity, disorganization, and inconsistency [10]. This can be particularly problematic on some challenging study types, such as magnetic resonance imaging (MRI) evaluation of brain tumors. Specifically, it has been a continued challenge for radiologists to accurately differentiate true tumor progression from the pseudoprogression of the tumor, due to tumor treatments such as radiation therapy and chemotherapy directly causing worsening of MRI imaging findings that can resemble tumor worsening [11]. To address these major concerns, in 2018, a Brain Tumor Reporting and Data System (BT-RADS) was introduced to provide neuroradiologists with a structured reporting method to promote uniformity and simplicity in their radiological reports of brain tumors [12, 13]. Similar structured reporting systems, such as the Breast Imaging and Liver Imaging Reporting and Data Systems, are widely utilized to standardize reports on those respective diseases [14]. BT-RADS utilizes an algorithm with 8

different scores ranging from 0 to 4, with zero representing a baseline image of the tumor and 4 representing high confidence of tumor progression [12]. These scores can be used by neuro-oncologists to help make clinical decisions after surgical treatment as well as predict patient clinical outcomes [15, 16]. Validating the use of BT-RADS for multi-institution and broader national and international use can improve patient care by fostering effective communication between neuroradiologists and referring physicians [17].

Current literature has demonstrated the usefulness of BT-RADS in a variety of manners. In two independent studies, one conducted at Emory University and another at an institution in Italy, neuroradiology departments were able to retrospectively analyze magnetic resonance imaging (MRI) scans to determine the interrater agreement of BT-RADS scores [18, 19]. At the Italian hospital, the study team found that BT-RADS reporting agreement was not affected by the radiologist's level of expertise, despite not utilizing the score in day-to-day practice. An online website with a scoring flowchart, templates for reports, as well as a score calculator potentially eased the learning curve for physicians not familiar with the algorithm [20]. In cases where physicians disagreed significantly on BT-RADS scoring, only 18% of those cases would have resulted in different management approaches [18]. In the study including both radiology residents and experienced radiologists as participants conducted at Emory University, where the algorithm had been in practice for over two years, an overall interrater agreement at 91% was observed [19]. This data suggests that the BT-RADS algorithm is relatively straightforward and able to be comprehended by physicians from a wide range of experiences. BT-RADS has also been shown to both qualitatively and quantitatively improve the clarity of and satisfaction with radiology reports. In a study analyzing the combined opinion of non-radiologists and radiologists on BT-RADS implementation, providers were significantly more satisfied with post-

implementation BT-RADS reports and believed that the scores helped facilitate research and education [17]. A separate quantitative analysis of radiology reports found that reports using BT-RADS templates significantly reduced hedge word usage, overall word count, as well as addendum usage in templates when compared to free pose reports [21]. This reduction in unnecessary vocabulary corroborates the perceived reduction of complexity and improved comprehension. Finally, a third study completed at Emory University found that BT-RADS scores inherently can help clinicians estimate patient survival and determine the need for changes in tumor management in patients with high-grade gliomas [15]. This predictive information is summarized in a hazard model which estimated the risk of death given BT-RADS score, IDH mutation presence, and MGMT methylation presence. These works have been instrumental in demonstrating the accuracy and clinical relevance of BT-RADS implementation on its road to widespread usage.

However, no study has reviewed the implementation of BT-RADS in actual clinical practice, but Emory Healthcare's longstanding usage of the system presents a plentiful source of scans. This study conducts an analysis of thousands of MRI scans to understand how certain factors, such as individual interpreting physicians and different tumor types, affect the distribution of BT-RADS scores. From previous studies demonstrating high-interrater agreement, it can be expected that during independent usage of the study on a random set of MRI scans, well-trained radiologists should have similar score distributions [18]. Between the two most common tumor types present in Emory's patient population, astrocytomas and oligodendrogliomas, the better prognosis of low-grade oligodendrogliomas in comparison to astrocytomas suggests oligodendrogliomas should have a more favorable score distribution [22, 23]. In addition, for follow-up MRIs on tumors with favorable mutations such as an IDH

mutation or MGMT methylation which confer a better prognosis, it can be expected that those mutations will have BT-RADS scores that are lower than the overall population [24, 25]. As such, the study team proposes three main hypotheses for this study.

1) BT-RADS score distributions should retain a high degree of similarity between individual physicians.

2) Astrocytomas (including glioblastoma (GBM)) should have a distribution with a higher proportion of scores indicating progression compared to oligodendrogliomas.

3) IDH mutated and MGMT methylated tumors should have a higher proportion of favorable scores compared to non-IDH mutated and MGMT unmethylated tumors, respectively.

MATERIALS AND METHODS

Patient Population

Consecutive imaging reports of brain MRIs interpreted using the BT-RADS system were obtained from Emory Healthcare locations between January 1st, 2021, and September 20th, 2024. All reports using the BT-RADS system were collected using Philips PerformanceBridge (Koninklijke Philips NV, Amsterdam, Netherlands) by searching for reports with the text of BT-RADS scores ("BT-0" OR "BT-1a" OR "BT-1b" OR "BT-2" OR "BT-3a" OR "BT-3b" OR "BT-3c" OR "BT-4") in them. All MRIs were of brain tumors, either those that originated in the brain or metastasized in the brain. Both inpatient and outpatient scans were included. MRI procedures included those with and without contrast as well as perfusion. Scans were excluded from the analysis pool if errors were detected in BT-RADS usage, such as assigning multiple scores, not assigning a score, or assigning a non-existent score.

Clinical Interpretation

Brain MRIs in patients with a diagnosis of brain tumor were interpreted during routine clinical care at Emory University. Individual faculty radiologists are assigned to a physician duty schedule in which they are assigned to read inpatient or outpatient imaging. Scans are interpreted by radiologists in chronological order of when the images were obtained, with the radiologist completing a text radiology report using a voice dictation system (Powerscribe, Microsoft, Bellevue, WA). Report templates specific to brain tumor interpretation were available, and faculty assigned BT-RADS scores based on previously described criteria [12]. Faculty radiologists frequently work with resident or fellow physicians training in radiology. These physicians in training may generate an initial report which is then reviewed and approved by the

faculty physician. A scan was counted as read by the faculty if they read the study with the assistance of a trainee physician, but trainee physicians were not included in the analysis. To minimize variation from physicians who interpreted smaller numbers of scans, only individual readers interpreting 100 or more scans utilizing the BT-RADS system in the study period were included in the physician score distribution portions of the analysis.

Demographic and Tumor Data Collection

Retrospective chart review was conducted through Epic 10.9 (Epic Systems Corporation, Wisconsin, United States) to determine patient demographics, tumor type, and tumor mutational burden. Review was conducted using oncology and neurology notes, as well as lab report results from both Emory and external organizations. Special attention was made to identify IDH mutation and MGMT mutation presence due to previous studies noting them as a determinant of BT-RADS survival indication [15].

Statistical Methodology

Data was cleaned and analyzed using StataNow/BE ver. 18.5 (StataCorp LLC, Texas, United States). The primary statistical test for physician score distribution was performed using the non-parametric chi-squared tests of independence, comparing the physician's rate of assignment for each BT-RADS score against the overall rate of assignment of that score for the entire data set. A further analysis was done by grouping scores based on their associated management recommendations. Scores 1a, 1b, and 2 were grouped into "continued follow-up with no management change." Scores 3a and 3b were grouped into "decreased time interval of follow-up." Finally, scores 3c and 4 were grouped into "consider a change in management." Each

recommendation group was again compared against each score in the overall distribution. A final analysis was made on the associated management recommendation analysis by removing scores of 0 which were associated with new scans, and was the only score not associated with a follow-up image. To analyze the distributions at each score, chi-squared tests of independence were run at each value as with the physician score distribution. In all analyses, the score distributions were broadly compared against the overall score distribution, again using a larger table of chi-squared tests of independence.

RESULTS

Overall Study Population Characteristics

A total of 4246 MRIs of brain tumors were included in this study from 928 unique patients, representing an average of 4.6 scans per patient. The average age of the patient at time of MRI scan was 50.1 ± 15.0 years with 2162 (50.9%) of scans being on female patients. The most common tumor types scanned were astrocytoma n = 2519 (59.3%) followed by oligodendroglioma n = 820 (19.3%) and then medulloblastoma and pilocytic astrocytomas, both at n = 111 (2.6%) each. Of the 4246 MRIs, an IDH mutation was present in 1542 (36.3%) scans and MGMT methylation was present in 1578 (37.2%) scans. Twelve board-certified neuroradiologists read at least 100 scans utilizing the BT-RADS system in the study period. Of the 12 physicians included in the score distribution analysis, they read a combined total of n = 3081 (72.6%) scans for an average of 256.8 ± 156.5 scans each (Table 1).

Overall Population BT-RADS Score Distribution

Of all BT-RADS scores collected across Emory Healthcare, score 2 was the most common with 2104 (49.6%) scans, followed by score 3b with 535 (12.6%) scans, and then score 3c with 411 (9.7%) scans. New scans, represented by score 0, as well as scores 1a and 4, sat similarly at 5.3%, 5.5%, and 5.9% of all scans, respectively. Pseudoprogression, score 3a, and pseudoresponse, score 1b, were 7.2% and 4.4% respectively (Figure 1).

Physician BT-RADS Score Distribution and Deviation

When comparing the physician distributions broadly, of the 12 radiologists included in the study, 6 (50.0%) had distributions that were not significantly different from the overall

distribution. When the analysis was broken down to comparisons at each score level, 5 (41.7%) had no significant deviation at any BT-RADS score from the overall population distribution (Table 2, Figure 2). A total of 19 instances of deviation were noted over 12 physicians, for an average of 1.6 ± 1.9 scores having significant deviation per physician. Physician 7 deviated at the most scores, assigning six scores at a significantly different rate than the overall distribution. All scores saw at least 1 physician assign it at a different rate than the overall distribution, for an average of 2.4 ± 0.5 physicians deviating per score. BT-RADS scores of 0, 3c, and 4 had the most physicians deviating at three physicians each. 19 instances of deviation out of 96 scoring rates indicated that physicians assigned BT-RADS scores at the same rate as the overall distribution for 80.2% of the categories. The analysis was additionally modified to combine scores into four groups based on the BT-RADS score's management recommendation (Table 3, Figure 3). Again, 5 out of 12 radiologists had no significant deviation from the overall recommendation rate at any BT-RADS level, and a total of 12 instances of deviation were noted for an average of 1.0 ± 0.9 score groups having significant deviation per physician. At each BT-RADS management recommendation level, an average of 3.0 ± 0.0 physicians deviated. There were 12 instances of deviation out of 48 scoring rates. A final analysis was done on the management recommendation version, where new scans with score zero were removed from the distribution (Table 4, Figure 4). This time, 7 out of 12 radiologists had no significant deviation from the overall recommendation rate at any BT-RADS level, and a total of 8 instances of deviation were noted for an average of 0.7 ± 0.9 score groups having significant deviation per physician. Now, at each BT-RADS management recommendation level, an average of 2.7 ± 0.6 physicians deviated.

Astrocytoma vs. Oligodendroglioma BT-RADS Score Distribution

Astrocytomas and oligodendrogliomas were the two most common tumor types in the data set, comprising 78.6% of all tumors scanned in the study. Score 1a, true tumor improvement, was the only score that had no significant difference between the tumor types. Oligodendrogliomas were significantly more likely to be assigned a pseudoresponse score, 1b (17.6% vs 5.4%, $p < 0.001$) as well as an unchanged status score of 2 (54.8% vs 41.5%, $p < 0.001$). Astrocytomas had significantly higher rates at all progressive scores. For scores recommending a management change, astrocytomas were higher, score 4 (7.8% vs 2.2%, $p < 0.001$), and 3c (11.5% vs 6.8%, $p < 0.01$). For scores recommending a decrease in follow-up interval, astrocytomas were also more prevalent, score 3a (8.7% vs 2.9%, $p < 0.001$) and score 3b (15.6% vs 9.5%, $p < 0.001$). A two by eight chi squared table demonstrated the overall difference between tumor type distributions to be statistically significant, $\chi^2 = 1199.9$, df = 7, $p < 0.0001$ (Figure 5).

IDH mutant (IDH+) vs. IDH wild-type (IDH–) BT-RADS Score Distribution

1542 scans of IDH+ tumors were compared against 2553 scans of IDH– tumors. 151 scans had indeterminate IDH status. As in the tumor type comparison, the only score that had no significant assignment rate difference between the IDH types was 1a. Notably, IDH+ tumors were much more likely to have unchanged status, BT-RADS score 2 (63.2% vs 41.9%, $p < 0.001$). IDH– tumors were more commonly assigned scores that indicated progression, including tumor progression scores 4 (8.0% vs 3.5%, $p < 0.001$) and 3c (11.0% vs 7.4%, $p < 0.01$), as well as indeterminate progression score 3b (15.0% vs 10.8%, $p < 0.01$) and finally pseudoprogression score 3a (8.0% vs 4.5%, $p < 0.001$). A two by eight chi squared table demonstrated the overall

difference between IDH distributions to be statistically significant, χ^2 = 304.4, df = 7, p < 0.0001 (Figure 6).

MGMT methylated (MGMT+) v.s. MGMT unmethylated (MGMT–) BT-RADS Score Distribution

A total of 1578 scans of MGMT+ tumors were compared against 2517 scans of MGMT– tumors. No significant difference was observed in the proportion of scans assigned scores 1a, 3c, or 4. More MGMT– tumors were assigned scores of 0 new scan (6.8% vs 4.1%, p < 0.01), and 2, unchanged scan (53.1% vs 44.8%, p < 0.001). A higher proportion of MGMT+ tumors fell into 1b pseudoresponse (5.2% vs 3.7%, p < 0.05) and 3a pseudoprogression (8.9% vs 5.4%, p < 0.001). For 3b, an indeterminate mix between increasing tumor burden and pseudoprogression, a higher proportion of MGMT+ tumors was also observed (15.8% vs 11.9%, p < 0.01). A two by eight chi squared table demonstrated the overall difference between MGMT distributions to be statistically significant, χ^2 = 557.76, df = 7, p < 0.0001 (Figure 7).

DISCUSSION

Accurately understanding how brain tumors change between MRI scans is critical for physicians to make decisions regarding patient management. If a patient's scan is worsening, the treatment team will likely decide on a new treatment, such as a new chemotherapy, new surgery, or repeat radiation. Previously, the unstructured nature of radiology reports on brain tumors could result in lengthy and uncertain information, creating an inefficient flow of information between physicians and making decision-making challenging. BT-RADS has shown promise as a reporting structure which can promote uniformity and consistency across reports, reducing the use of hedge words in reports and increasing provider satisfaction with the radiology reports [17, 21]. To continue demonstrating the applicability of BT-RADS in clinical practice, this study builds off previous work which has shown that BT-RADS is easy to learn and has high levels of interrater agreement.

The 4246 scans and 12 physicians in this study comprise the largest set of BT-RADS scores studied before. Understanding if BT-RADS score distributions are consistent across physicians when independently reviewing MRI scans is critical to validating the clinical utility of BT-RADS in a realistic practice environment. Demonstrating that BT-RADS can maintain a similar score distribution across experienced physicians further strengthens the notion that reader usage of the scale remains similar when in an uncontrolled environment. Furthermore, understanding how BT-RADS score distributions are affected by major factors such as tumor types and genetic mutations can help radiologists realize the inherent information contained in assigned scores.

Previous studies on interrater agreement of BT-RADS score assignment in a retrospective review design at Emory found that six radiologists demonstrated high levels of agreement with a Gwet index of 0.83, performing comparatively against other RADS systems already adopted for

widespread use [19, 26, 27]. This study sought to continue the exploration of how individual physicians utilized BT-RADS in actual clinical practice, assuming a random distribution of MRI scans assigned to them to be read. At the start of this study's scan inclusion window, physicians at the institution had been using the scale for about two years and should have good overall familiarity with the system. Our hypothesis was that individual radiologists have similar distributions of BT-RADS score assignments when compared to their peers and to the overall distribution at Emory Healthcare [20]. In 80.2% of category comparisons, the independent usage of BT-RADS produced similar score distributions between the radiologists, indicating overall very good agreement between readers.

In the design of BT-RADS, some scores reflect different degrees of uncertainty but have the same associated management recommendation. Because these scores may result in the same patient care decision, physicians may be more tolerant of variation within the scoring if management recommendations remained the same. To account for this leeway, the analysis was approached from another angle where BT-RADS scores were grouped based on their 4 associated management recommendations, to ensure that even if there was a slight deviation in the score assignment, the management meaning of the score for physicians reviewing the report remained unchanged. Upon combining the scores, 75% of the comparisons of recommendation rates exhibited no significant difference, which was slightly lower than the 80.2% of comparisons between scores. Finally, the study team was concerned with the significant difference in some physicians for the score assignment of 0. Since score 0 is less open to interpretation in its indication of a new scan with no prior imaging, this significant difference in proportion could be differences in the understandings of rules, such as discarding the BT-RADS scale for new scans instead of assigning the appropriate score. Thus, including score 0 in the

distribution could affect the proportions of other BT-RADS scores. For example, when including zero scores for new scans, physician 7 deviated at six out of seven individual BT-RADS scores, but upon combining scores based on management recommendation then removing zeros, physician 7 did not significantly deviate from the distribution at any level. Repeating this analysis, it was found that 77.8% of score comparisons found no significant difference between individual physicians and the overall distribution. An Italian study retrospectively analyzing a much smaller sample of 588 scans found that discrepancies between readers resulted in a different management recommendation about 18% of the time, comparable to the 22.2% observed in this study [18]. The slightly higher rate of management deviation could be attributed to the single review nature of this study, where a single radiologist makes a final decision on every scan's BT-RADS score, where the Italian study's retrospective nature allowed for the same set of scans to be reviewed by each participating physician.

The study team was additionally interested in the possibility of classifications affecting the distribution of BT-RADS scores. The two most common tumor types, astrocytomas and oligodendrogliomas, comprised around 80% of the total tumors scanned in this study and were included for comparison. Oligodendrogliomas are defined by IDH mutations and 1p/19q chromosomal deletion, a genetic profile that is associated with better responsiveness to treatments such as chemotherapy as well as longer overall survival times for patients [28, 29]. As a result, patients with oligodendrogliomas have significantly better prognoses when compared to patients with other types of gliomas of the same grade. In Figure 5, oligodendrogliomas clearly tend to have higher rates of score 1b and 2, indicating imaging improvement as well as stability, as compared to the much higher rate of progressive scores, 3a through 4, that astrocytomas have. The overall distribution of BT-RADS scores for the two different types of tumors also remains

significantly different, possibly indication of how BT-RADS can reflect differences in underlying tumor histology.

IDH and MGMT genetic information are well-documented predictors for brain tumor prognosis [30]. A previous study on BT-RADS built a Cox regression model incorporating MGMT and IDH tumor characteristics alongside BT-RADS score to predict the risk of death and found that unfavorable MGMT status significantly increased the risk of death for each increase in BT-RADS score [15]. This study sought to understand if, over a broad population of MRI scans, the distribution of BT-RADS scores would be affected by different genetic markers of brain tumors.

Patients with IDH1 mutated tumors of any grade have been shown to have significantly longer survival time compared to those with IDH wild-type tumors, due to the IDH mutation impairing the tumor's ability to have a protective antioxidant system [31]. Our hypothesis was that IDH– tumors would have higher rates of progressive score, while IDH mutated tumors would remain more stable. The difference in stability is clearly supported when analyzing the BT-RADS score of 2 in Figure 6, where IDH+ tumors are assigned a score of 2 63.2% of the time while IDH– tumors are assigned the same score only 41.9% of the time ($p < 0.001$). The genetic advantage of patients with IDH+ tumors would likely mean that the tumors would be less likely to be assigned aggressive BT-RADS scores of 3a through 4, of which IDH+ is lower than IDH– at every level ($p < 0.01$). The effect of the IDH+ mutation is a clear skew of the BT-RADS score distribution, indicating the score is reactive to significant genetic mutations which can affect the prognosis of the tumor. This confirms prior work indicating that IDH mutated tumors have lower progression rates.

MGMT is a DNA repair enzyme that plays a role in producing chemoresistance for tumors [7]. As a result, the detection of MGMT methylation is a biomarker that can indicate a favorable response to alkylating chemotherapy treatment, leading to higher rates of overall survival and tumor response to chemotherapy when compared to MGMT unmethylated patients [32, 33]. Thus, it can be expected that MRI scans of MGMT+ tumors should show fewer progressive BT-RADS scores in comparison to MGMT– tumors. A significant ($p < 0.01$) increase in 3a and 3b scores was noted for the MGMT+ group (Figure). 3a and 3b scores indicate imaging worsening from the last follow-up like due to treatment effects including radiation therapy and medication, or are indeterminant, respectively. Patients with MGMT methylated tumors are known to have higher rates of pseudo-progression, a situation where imaging findings are worsened by creating imaging abnormalities that are not due to tumor progression and are difficult to differentiate from the tumor itself [34, 35]. Furthermore, MGMT+ scans were more likely to be assigned 1b, or pseudoresponse, likely reflecting higher rates of these patients being treated with new medications such as bevacizumab, which can result in imaging improvement. In total, it is inconclusive if MGMT status significantly shifts the overall distribution of BT-RADS scores toward more favorable scores, but MGMT+ tumors appear to have a higher number of scores associated with pseudoresponse and pseudoprogression, which can better inform neurooncologists if the current management of patients is effective, especially if care plans involving temozolomide and chemotherapy are developed to take advantage of the patient's genetic status [36]. This inherent information contained within the BT-RADS score in conjunction with patient history can clearly and quickly convey the reasoning behind imaging worsening to justify further follow-up or be the basis for a change in management.

Our study has several limitations that must be acknowledged. One limitation is that the study cannot guarantee the true randomness of patients and scans assigned to reading radiologists. At Emory Healthcare, neuroradiologists read scans sequentially as they are performed on days they are on clinical service. As a result, all radiologists may not see an equivalent patient population. To mitigate this possible bias, the study team excluded radiologists who read less than 100 scans to create a sample size that is large enough to reduce the chance of physicians having a systematic bias in cases they interpreted, essentially creating a "pseudo-randomness." However, controlling the study so that true random assignment is achieved is also undesirable, as this would deviate from the study's original purpose at understanding BT-RADS performance in actual day-to-day clinical practice. An additional limitation is that collecting the data set for this project could have led to the unintentional exclusion of some scans. Reports were collected by identifying all the reports which contained a BT-RADS score as denoted by the string "BT-x" (with x being a score). However, this could have excluded scans where BT-RADS was deleted or erroneously used without the BT prefix. While the study team expected radiologists to be familiar with the scoring system due to its implementation for over two years prior to the scan inclusion period as well as the reasonable learning curve [17], there is still a possibility that radiologists included in the study could have misused the system. A more comprehensive search of all patients with a diagnosis of brain tumor could potentially to avoid this problem and to accurately document "BT-RADS misuse" in their distribution analysis.

More work needs to be done to continue validating BT-RADS for widespread adoption across radiological societies and additional healthcare systems. One way to improve uniformity of BT-RADS application is to develop more structured materials for teaching system use. These could ease the implementation process at other healthcare institutions, and routine in-service

using these materials could reduce variation in scale implementation over time. Training guides and educational videos should be created to walk radiologists through the algorithm to ensure strict and uniform adherence for interpretation. As BT-RADS is implemented across more healthcare systems and continues to be used at Emory Healthcare, time series analyses of tumor types and genetic status may help understand how physicians adapt to the BT-RADS implementation. Year by year comparisons of score distributions could be made to discern if the distribution of distributions becomes more variable with time or becomes more uniform. In addition, as brain tumor data from other healthcare systems utilizing BT-RADS grows, comparisons of BT-RADS score distributions between different populations can be conducted. Previous work has shown that brain tumors affect certain demographics differently, and comparisons between regions such as Atlanta and the San Francisco Bay Area could yield interesting insights as to how BT-RADS score distributions capture the difference in populations [37]. Furthermore, as BT-RADS enters its seventh year at Emory, additional statistical analyses could be done to create acceptable score bands, essentially confidence intervals for different BT-RADS scores to give physicians a guideline on how many scans they should expect to be in each range. If physicians deviate too much, this could flag their reports for additional review or intervention to ensure that radiologists continue to give concise and uniform reports on brain tumors.

BT-RADS continues to demonstrate strong usage similarities by individual radiologists in independent usage across a single healthcare system. In comparisons against the overall distribution, physician assignment rates of scores had good agreement, over 80% of the time. Differences in tumor progression affected by tumor type, genetic differences, and molecular

markers are reflected in BT-RADS scoring, promising nuance with structure to enable accurate and imaging-informed management of brain tumor patients.

TABLES AND FIGURES

Study characteristics	
Patients	928
Total MRI scans	4246
Scans per patient	4.6
Population Demographics	
Age, mean years ± SD	50.1 ± 15.0
Female, n (%)	2162 (50.9)
Common Tumor Types	
Astrocytoma, n (%)	2519 (59.3)
Oligodendroglioma, n (%)	820 (19.3)
Medulloblastoma, n (%)	111 (2.6)
Pilocytic Astrocytoma, n (%)	111 (2.6)
Common Mutations	
IDH mutation, n (%)	1542 (36.3)
MGMT methylation, n (%)	1578 (37.2)
Physicians	
Physicians included	12
Scans read, mean ± SD	256.8 ± 156.5

Table 1. General demographic information regarding study patient population. Values in parentheses are percentages of the study population age refers to patient age at time of scan completion. IDH = Isocitrate Dehydrogenase. MGMT = O-6-methylguanine-DNA-methyltransferase.

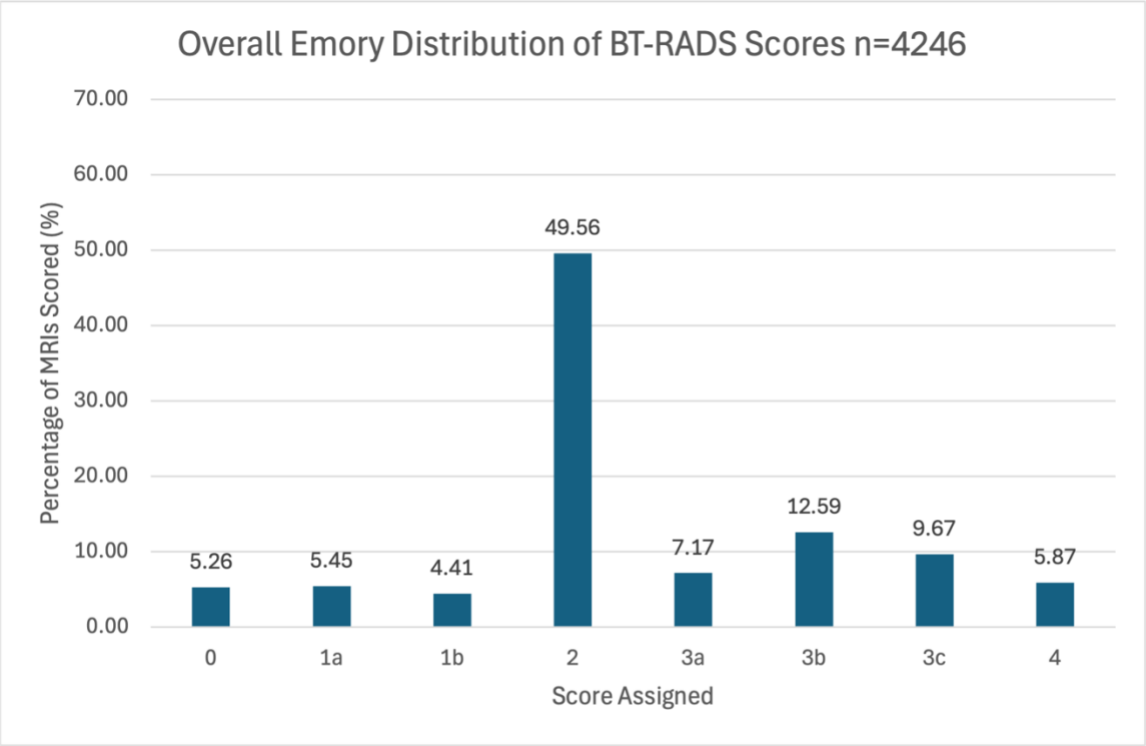

Figure 1. Overall distribution of BT-RADS scores at Emory Healthcare during the study period. Values are expressed in percentage points.

Table of BT-RADS Score Distributions and Comparisons for Physicians

reader	1	2	3	4	5	6	7	8	9	10	11	12
0	5.19	4.29	2.44	2.78	8.24	5.58	10.50	7.69	3.30	8.26	3.48	3.64
p-value	0.9396	0.4178	0.0248	0.0642	0.0336	0.8378	0.0015	0.141	0.2427	0.148	0.3969	0.4508
1a	5.33	7.51	2.44	3.47	6.09	3.72	10.50	6.67	4.95	4.96	7.83	2.73
p-value	0.8984	0.0976	0.0184	0.1476	0.6494	0.2722	0.0026	0.4652	0.7707	0.8147	0.2699	0.212
1b	4.15	7.51	5.49	4.86	5.02	2.79	1.00	2.05	3.85	2.48	6.96	3.64
p-value	0.759	0.0065	0.3627	0.7197	0.6321	0.255	0.0196	0.1125	0.718	0.3052	0.192	0.6972
2	47.56	51.74	55.79	55.21	39.78	53.02	46.50	53.85	50.00	43.80	50.43	41.82
p-value	0.619	0.4195	0.0297	0.0635	0.0015	0.3223	0.3977	0.2414	0.9075	0.2115	0.8539	0.109
3a	8.30	6.70	7.32	2.78	7.53	6.05	6.00	5.13	9.89	16.53	5.22	7.27
p-value	0.2953	0.7353	0.9193	0.0044	0.8216	0.5332	0.5295	0.2776	0.1667	0.0001	0.4233	0.968
3b	13.93	13.94	10.37	8.33	15.41	15.35	7.50	11.28	11.54	13.22	13.04	17.27
p-value	0.3327	0.4528	0.2404	0.0333	0.1716	0.2361	0.0326	0.5891	0.6754	0.8369	0.8859	0.1457
3c	10.81	7.51	7.01	16.32	9.32	8.37	4.00	7.18	10.99	7.44	10.43	18.18
p-value	0.3554	0.1725	0.1131	0.0003	0.8479	0.528	0.0073	0.2476	0.5562	0.4118	0.7858	0.0032
4	4.74	0.80	9.15	6.25	8.60	5.12	14.00	6.15	5.49	3.31	2.61	5.45
p-value	0.2401	0.0001	0.0168	0.791	0.0637	0.6472	0.0001	0.8709	0.8307	0.2349	0.1395	0.8531
overall p-value	0.6347	0.0001	0.0014	0.0001	0.0258	0.6244	0.0001	0.2831	0.7841	0.0041	0.4971	0.0565

Table 2. Each row represents a BT-RADS score, and each column represents a physician. Rows are further alternating between proportion of BT-RADS score and p-value. The bottom row is a comparison of the entire distribution. Significance is indicated in orange ($p < 0.05$) and red ($p < 0.01$).

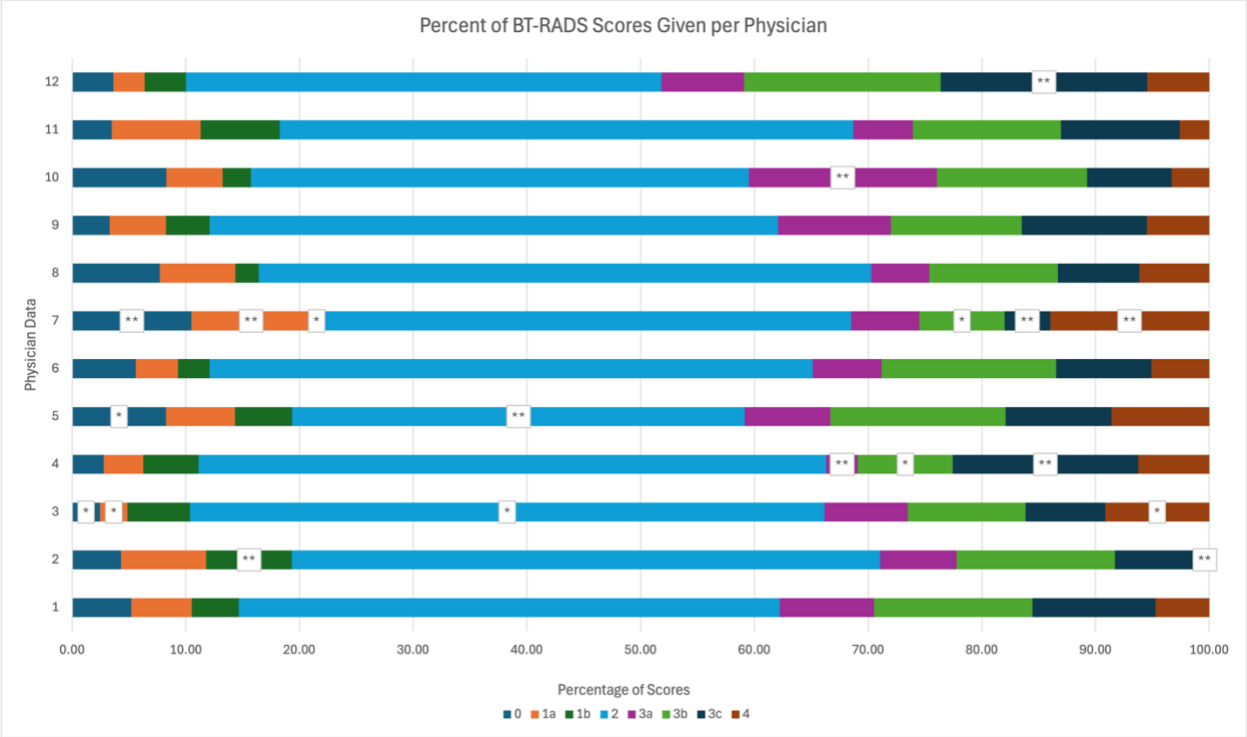

Figure 2. A visualization of Table 2. Each row represents a physician, and each color is a BT-RADS score, with the size of the color band indicating the proportion of that score. All bands total to 100. Significance is indicated by * ($p < 0.05$) and ** ($p < 0.01$).

Table of BT-RADS Score Associated Management Recommendation Distributions and Comparisons for Physicians

reader	1	2	3	4	5	6	7	8	9	10	11	12
no prior	5.19	4.29	2.44	2.78	8.24	5.58	10.50	7.69	3.30	8.26	3.48	3.64
p-value	0.9396	0.4178	0.0248	0.0642	0.0336	0.8378	0.0015	0.141	0.2427	0.148	0.3969	0.4508
continue follow-up, no change	57.04	66.76	63.72	63.54	50.90	59.53	58.00	62.56	58.79	51.24	65.22	48.18
p-value	0.2408	0.0056	0.1270	0.1689	0.0050	0.9768	0.6874	0.3839	0.8633	0.0707	0.2119	0.0178
decrease follow-up interval	22.22	20.64	17.68	11.11	22.94	21.40	13.50	16.41	21.43	29.75	18.26	24.55
p-value	0.1402	0.6863	0.3585	0.0003	0.1995	0.5589	0.0287	0.2481	0.5824	0.0069	0.6881	0.2150
consider management change	15.56	8.31	16.16	22.57	17.92	13.49	18.00	13.33	16.48	10.74	13.04	23.64
p-value	0.9947	0.0002	0.7692	0.0017	0.2919	0.4149	0.3516	0.4017	0.7349	0.1486	0.4629	0.0215

Table 3. Each row represents an associated management recommendation for BT-RADS scores, and each column represents a physician. Rows are further alternating between proportion of management recommendation and p-value. Significance is indicated in orange ($p < 0.05$) and red ($p < 0.01$).

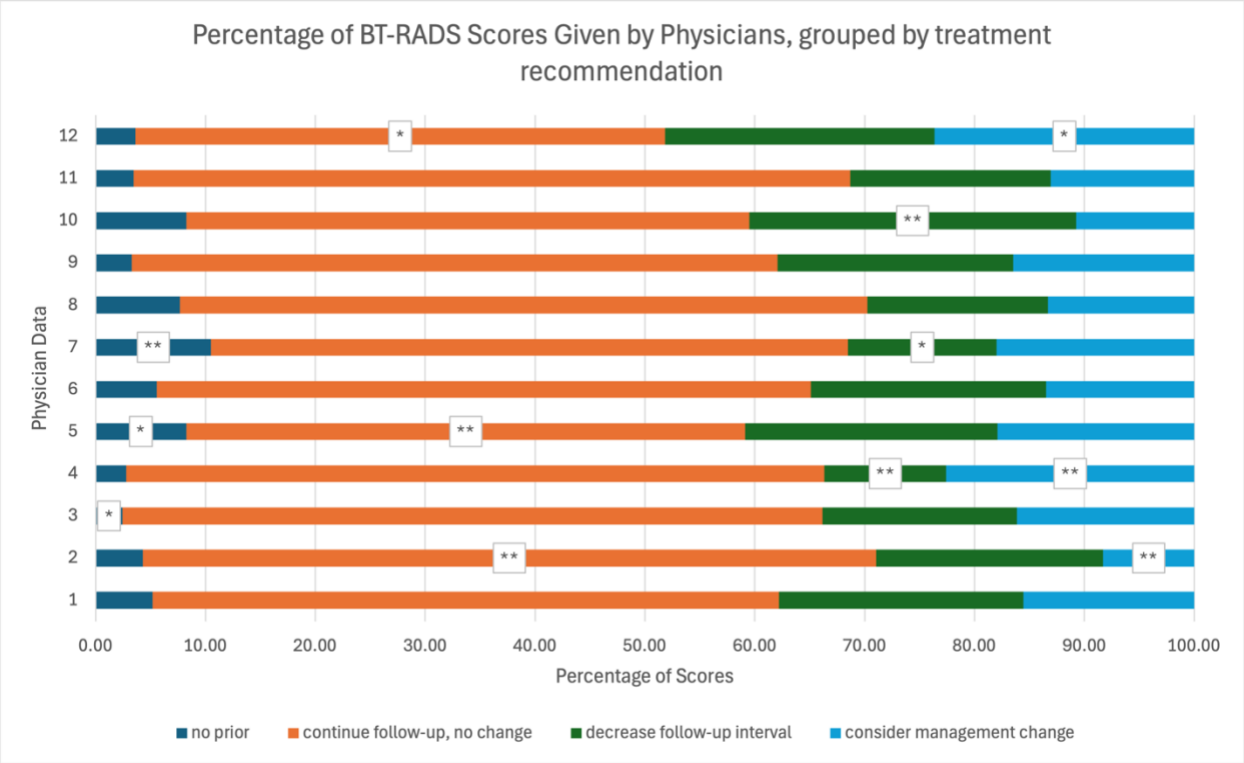

Figure 3. A visualization of Table 3. Each row represents a physician, and each color is a grouping by BT-RADS score's implied treatment recommendation, with the size of the color band indicating the proportion of that score. All bands total to 100. Significance is indicated by * ($p < 0.05$) and ** ($p < 0.01$).

Table of BT-RADS Score Associated Management Recommendation Distributions and Comparisons for Physicians, Disregarding New Scans (Score 0)

reader	1	2	3	4	5	6	7	8	9	10	11	12
continue follow-up, no change	60.16	69.75	65.31	65.36	55.47	63.05	64.80	67.78	60.80	55.85	67.57	50.00
p-value	0.2129	0.0084	0.3580	0.3786	0.0202	0.9267	0.5751	0.1700	0.6045	0.1397	0.2979	0.0076
decrease follow-up interval	23.44	21.57	18.13	11.43	25.00	22.66	15.08	17.78	22.16	32.43	18.92	25.47
p-value	0.1384	0.7520	0.2458	0.0001	0.1157	0.5387	0.0615	0.3187	0.6782	0.0033	0.6195	0.2500
consider management change	16.41	8.68	16.56	23.21	19.53	14.29	20.11	14.44	17.05	11.71	13.51	24.53
p-value	1.0000	0.0001	0.9444	0.0033	0.1934	0.4252	0.1928	0.4843	0.8226	0.1859	0.4150	0.0267

Table 4. Each row represents an associated management recommendation for BT-RADS scores ignoring the new scan group, and each column represents a physician. Rows are further alternating between proportion of management recommendation and p-value. Significance is indicated in orange ($p < 0.05$) and red ($p < 0.01$).

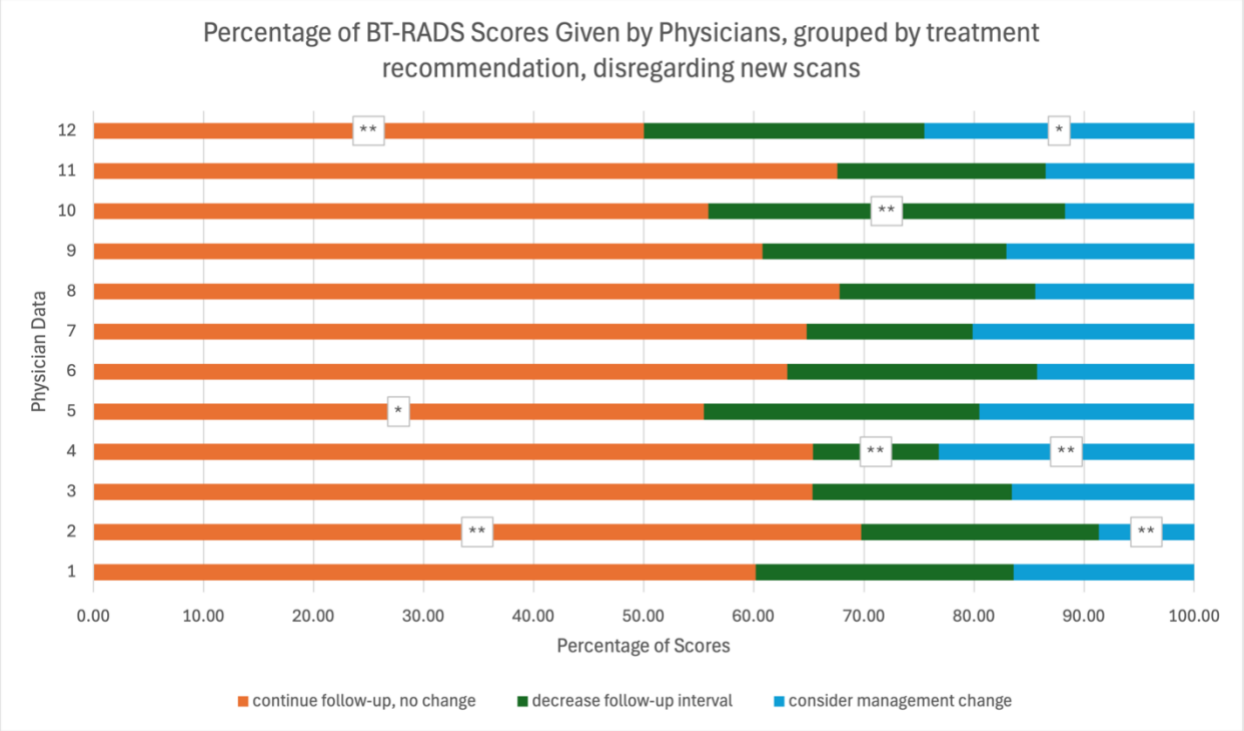

Figure 4. A visualization of Table 4. Each row represents a physician, and each color is a grouping by BT-RADS score's implied treatment recommendation, with the size of the color band indicating the proportion of that score. New scans are ignored. All bands total to 100. Significance is indicated by * ($p < 0.05$) and ** ($p < 0.01$).

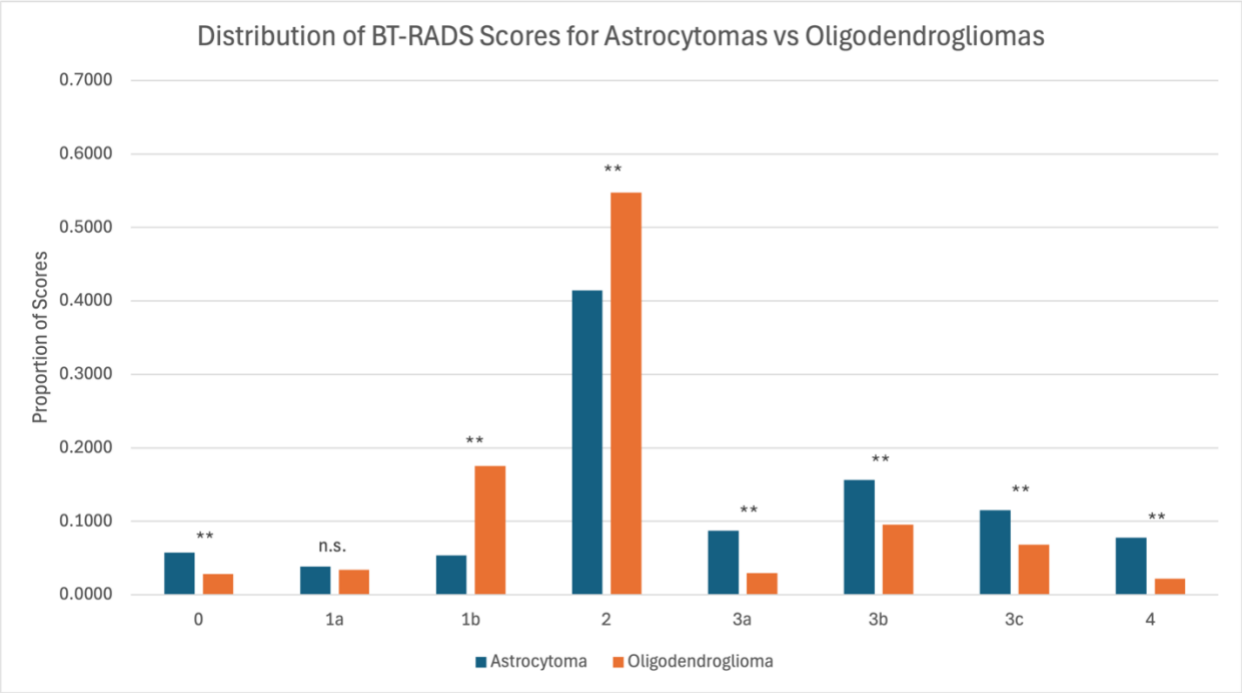

Figure 5. Comparison of astrocytoma against oligodendroglioma BT-RADS score assignment rates. Significance is indicated by n.s. (not significant) and ** ($p < 0.01$).

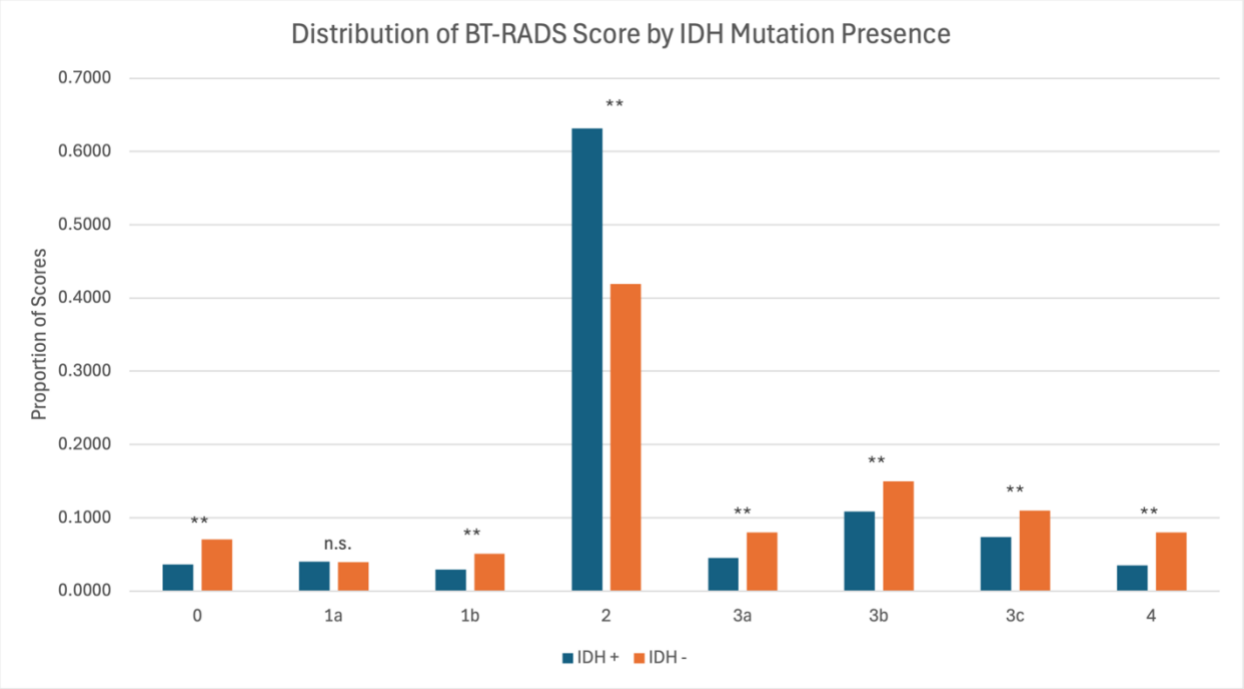

Figure 6. Comparison of tumors that are IDH mutated against IDH wildtype BT-RADS score assignment rates. Significance is indicated by n.s. (not significant) and ** ($p < 0.01$).

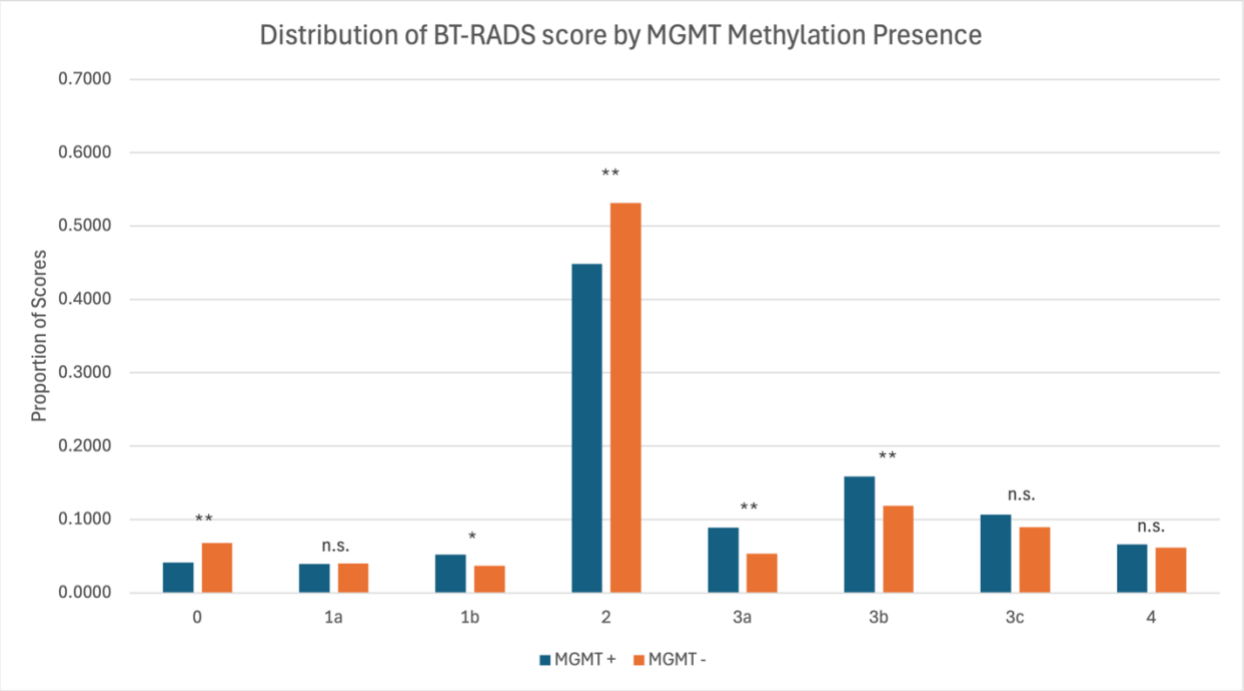

Figure 7. Comparison of tumors that are MGMT methylated against MGMT unmethylated BT-RADS score assignment rates. Significance is indicated by n.s. (not significant), * ($p < 0.05$), and ** ($p < 0.01$).

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