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INTEGRATING MRI AND CT IMAGING WITH MICROBIOLOGICAL DIAGNOSTICS IN THE EARLY DETECTION OF BRAIN ABSCESSES

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Abstract
Brain abscesses are critical intracranial infections that demand rapid and accurate diagnosis to prevent neurological deterioration and mortality. While magnetic resonance imaging (MRI) and computed tomography (CT) are central to identifying structural abnormalities and guiding early clinical suspicion, they often lack specificity in distinguishing abscesses from necrotic tumors or other ring-enhancing lesions. Microbiological testing, on the other hand, provides definitive etiological insight but is limited by delayed sample processing and potential false negatives in pre-treated patients. This study investigates the diagnostic value of a combined approach using MRI, CT imaging, and microbiological diagnostics in early-stage brain abscess detection. A prospective cohort of patients with suspected brain abscess underwent imaging protocols including diffusion-weighted imaging (DWI), susceptibility-weighted imaging (SWI), and contrast-enhanced CT, followed by microbiological testing such as Gram staining, culture, and PCR analysis. The integrated approach significantly improved diagnostic sensitivity and specificity compared to any single modality. MRI features such as the "dual rim sign" and restricted diffusion patterns showed a strong correlation with culture-confirmed pyogenic abscesses. Integration of imaging and microbiological data reduced diagnostic delay and enabled timely, pathogen-targeted therapeutic decisions. These findings highlight the clinical relevance of a multimodal diagnostic pathway and advocate for its incorporation into routine neuroinfectious disease management protocols.

Keywords: brain abscess, MRI, CT imaging, microbiological diagnostics, early detection

1. Introduction

Brain abscesses (BAs) are severe and life-threatening central nervous system infections that involve a focal accumulation of pus in the brain parenchyma, most commonly due to a synergy between microbial invasion, tissue necrosis, and host immune reaction (1). Although they are not very common, BAs are a neurosurgical emergency because they have an aggressive course and may lead

to permanent neurological dysfunction or death if untreated (2). The clinical presentation tends to be nonspecific, such as headache, fever, altered mental status, or focal neurological deficits, which makes early and correct diagnosis a daunting task (3,4).

Imaging is pivotal in the detection, localization, and characterization of brain abscesses. CT can detect early changes related to BAs, but in suspected cases, MRI should be preferred because it offers better imaging, particularly of the brain soft tissue and the ability to look at scans from many directions (5,6). Because of diffusion-weighted imaging (DWI), susceptibility-weighted imaging (SWI) and magnetic resonance spectroscopy (MRS), it is now easier to diagnose abscesses compared to other ring-enhancing lesions like necrotic glioblastomas and metastases (7,8). Restricted diffusion seen in the center of the lesion on DWI and the double-ring appearance from SWI are considered specific indications of pyogenic abscesses (9).

But radiological modalities, while very sensitive in detecting structural and morphological characteristics, tend to be lacking in the separation of the causative pathogen. Microbiological verification continues to be important to direct specific antibiotic therapy and minimize empirical treatment risks (10). Traditional techniques like Gram stain, aerobic and anaerobic cultures, and antimicrobial susceptibility tests are used regularly, but their sensitivity is often reduced in patients with a history of previous exposure to antibiotics or with fastidious organisms (11). This has generated growing interest in molecular diagnostics like 16S ribosomal RNA polymerase chain reaction (PCR) and metagenomic next-generation sequencing (mNGS), which allow both culturable and unculturable organisms to be identified directly from cerebrospinal fluid or abscess aspirates (12–14).

Combining microbiological information with imaging results provides a multimodal diagnostic paradigm that makes up for the deficiencies inherent in either technique in isolation. This strategy is part of the larger movement toward precision medicine, where therapy choices are more and more personalized according to particular anatomical, microbial, and clinical profiles (15). Large retrospective studies and case series have shown that an integrated diagnostic framework enhances the specificity of early diagnosis and facilitates timely neurosurgical planning (16). In addition, functional imaging modalities like positron emission tomography (PET) have been investigated to differentiate infectious from neoplastic lesions, even though their specificity in the case of neuroinflammation is limited (17).

Considering the clinical significance of early and precise diagnosis of brain abscesses, this research seeks to assess the diagnostic accuracy of an integrated diagnostic approach using advanced imaging (MRI, CT) and microbiological examination (culture, PCR) for early diagnosis and etiologic explanation of brain abscesses. We predict that the multimodal strategy will yield greater diagnostic accuracy, reduced time to diagnosis, and better therapeutic targeting than traditional single-modality assessment.

2. Materials and Methods

2.1 Study Design and Setting

This prospective, observational diagnostic performance study was undertaken at the Department of Neurosurgery and Radiology, an academic tertiary-care medical center. The duration of the study was 24 months and complied with the institutional research ethics rules as per the Declaration of Helsinki. Institutional Review Board approval had been obtained before initiation, and informed written consent was taken from all the enrolling patients or their legal guardians.

The study aimed to assess the diagnostic value of a multimodal diagnostic framework combining MRI, CT imaging, and microbiological testing in the early detection and characterization of brain abscesses. All patients presenting with clinical suspicion of intracranial abscess were screened using predefined inclusion and exclusion criteria.

2.2 Patient Enrollment

The inclusion criteria included adult patients (age ≥18 years) who presented within seven days of symptom onset with neurological signs indicative of intracranial infection (e.g., fever, focal neurological deficit, seizures, or altered mental status) and radiological suspicion of brain abscess.

Excluded were patients with a known history of neoplastic disease, cerebral infarction, previous craniotomy or treated abscess, or contraindications to MRI (e.g., pacemaker implantation, severe claustrophobia, or metallic implants).
Patients were admitted via the emergency department or referred from peripheral centers and were subjected to immediate neuroimaging and laboratory assessment. Baseline demographic and clinical information, such as Glasgow Coma Scale (GCS) score, immunological status, comorbidities, and prior antibiotic exposure, was noted.

2.3 Radiological Protocol

Every patient went through both non-contrast and contrast-enhanced CT and MRI at a high field strength. All patients were evaluated with 32-slice multidetector scanners by performing axial and coronal reconstructions. An MRI examination was done with a 1.5 Tesla scanner and included: T1-weighted images before and after contrast, T2-weighted images, fluid-attenuated inversion recovery (FLAIR), diffusion-weighted imaging (DWI), slight increase in DWI intensity seen on images with apparent diffusion coefficient (ADC) mapping, susceptibility-weighted imaging (SWI) and final enhanced scans after contrast. Radiological assessment was done in a blinded manner by two board-certified neuroradiologists independent of clinical and microbiological results. Joint consensus resolved discrepancies. Analysis of images concentrated on the morphology and presence of ring enhancement, central necrosis, diffusion restriction, the "dual rim sign," perilesional vasogenic edema, midline shift, and satellite lesions. A standard reporting template was used to ensure consistency.

2.4 Microbiological Workup

In those needing surgical treatment or stereotactic aspiration, intraoperative pus samples were taken and processed immediately under sterile conditions. In those not needing surgery, lumbar puncture was only done if there was no imaging contraindication.
Direct Gram stain, Ziehl–Neelsen stain for AFB, and aerobic, anaerobic, and fungal culture were done as part of microbiological analysis. Culture media used were blood agar, chocolate agar, and Sabouraud dextrose agar, with incubation extended to 14 days for anaerobes and fungi. Concurrently, molecular diagnostic techniques were used on aspirated material with 16S rRNA polymerase chain reaction (PCR) for the detection of broad-range bacteria and fungal-specific PCR analyses. Commercial kits (Qiagen™) were used for nucleic acid extraction, and sequencing was done on positive PCR products for identifying the species. Antimicrobial susceptibility testing (AST) was conducted by the CLSI-recommended broth microdilution method.

2.5 Integrated Diagnostic Framework

An algorithmic approach was applied to synthesize imaging and microbiological information. Radiologic findings for suspected abscess were smooth or multilobulated ring enhancement with central restricted diffusion and the "dual rim sign" on SWI. The cases were classified as: (i) true positive (radiologic and microbiologic concordance), (ii) false negative (radiology-negative, microbiology-positive), and (iii) microbiology-negative but imaging-positive (likely abscess). Synthesis interpretation was seen by a multidisciplinary board comprising neuroradiologists, microbiologists, neurologists, and infectious disease specialists.
This model mimicked real-life diagnostic decision-making in the clinical environment, in which imaging necessitates early treatment and microbiology validates the causative organism retrospectively.

2.6 Statistical Analysis

Sensitivity, specificity, PPV, NPV and area under ROC-AUC were counted for all ways of analyzing data and for the overall composite. Image interpretation by two different observers was compared using Cohen’s kappa coefficient. Correlations between the results of imaging (for example, thickness

of the abscess capsule or diffusion level) and the forms of pathogens were investigated using a Chi-square or Fisher's exact test as appropriate.
Variations in the typical patterns of diagnosis were studied by examining the results for people with different immune systems and in different brain regions. For a result to be considered statistically significant, p had to be lower than 0.05. Analysis of the data was done using IBM SPSS Statistics version 26.0.

3. Results

3.1 Patient Demographics and Clinical Characteristics

During the 24-month observation period, 80 patients were enrolled, all of whom fulfilled the inclusion criteria for suspected early-stage brain abscess. The cohort's mean age was 45.6 years (SD ±16.2), with a male predominance (58.8%, n=47) and a female representation of 41.2% (n=33). Thirty-five percent (n=28) of the patients were immunocompromised, such as those with diabetes mellitus, HIV infection, long-term corticosteroid therapy, or active malignancy. Most importantly, 46 patients (57.5%) had undergone empirical antibiotic therapy prior to microbiological sampling, a factor with proven deleterious effect on culture sensitivity.
Nearly a quarter (22 patients) of the total had a GCS of less than 8 which suggests a significant level of acute brain dysfunction. Deficits in one part of the nervous system were observed in 67.5% of patients, the most common being weakness affecting only one side of the body and palsies of some nerves in the head and neck. Patients most often came in with headaches (81.3%), fever (73.8%), and seizures (36.3%). Information on the distribution of key baseline demographic and medical details is shown in Table 1 below.

Table 1. Demographic and Clinical Profile of the Study Population (n = 80)

Variable	Value
Total number of patients	80
Mean age (years)	45.6 ± 16.2
Gender (Male/Female)	47 (58.8%) / 33 (41.2%)
Immunocompromised status	28 (35%)
Prior antibiotic use	46 (57.5%)
GCS < 8 on admission	22 (27.5%)
Focal neurological deficit	54 (67.5%)
Fever at presentation	59 (73.8%)
Headache	65 (81.3%)
Seizures	29 (36.3%)

The distribution of clinical features suggests that while classical symptoms such as headache and fever were prevalent, the presence of focal neurological signs and altered mental status were essential clinical flags prompting neuroimaging and early consideration of abscess. The immunological status of the patients, particularly in those with poor GCS and atypical presentations, significantly influenced the diagnostic complexity and radiological interpretation, necessitating the integration of advanced imaging modalities with microbiological workup in this cohort.

3.2 Diagnostic Performance of Individual and Integrated Modalities

The individual and integrated diagnostic performance of each modality—MRI, CT, and microbiological culture—was evaluated to determine the added value of integration. Sensitivity, specificity, PPV and NPV were compared to both the actual diagnosis and laboratory findings. MRI in isolation was shown to have a sensitivity of 87% and specificity of 79% and was successful in detecting the majority of cases of brain abscess, especially if there was restricted diffusion and the dual rim sign. CT, while easily available and frequently the initial imaging test done, had a reduced sensitivity of 71% and specificity of 65%, with significant shortcomings in the detection of early

cerebritis and minor capsule formation. Microbiological examination had the highest specificity (89%) but had a reduced sensitivity (68%), mainly caused by previous empirical antibiotic treatment, which most probably resulted in culture-negative results. The combined diagnostic model, with the integration of results from MRI, CT, and microbiology, had the best diagnostic measures in all the categories. Sensitivity was 95%, specificity was 91%, PPV was 94% and NPV was 93% for the integrated strategy, far above the values of any of the single diagnoses. These findings emphasize the clinical value of a multimodal approach to enhancing early detection rates and diagnostic accuracy for brain abscesses. Moreover, Figure 1 bar graph reveals comparative diagnostic statistics by modalities and indicates that the combined method obtains the highest levels of sensitivity, specificity, PPV, and NPV as compared to MRI, CT, and microbiology alone.
The complete diagnostic accuracy profile of each modality is presented in Table 2.

Table 2. Diagnostic Performance of Imaging and Microbiological Modalities

Modality	Sensitivity	Specificity	PPV	NPV
MRI Alone	87%	79%	84%	82%
CT Alone	71%	65%	69%	67%
Microbiology Alone	68%	89%	86%	75%
Integrated Approach (MRI + CT + Microbiology)	95%	91%	94%	93%

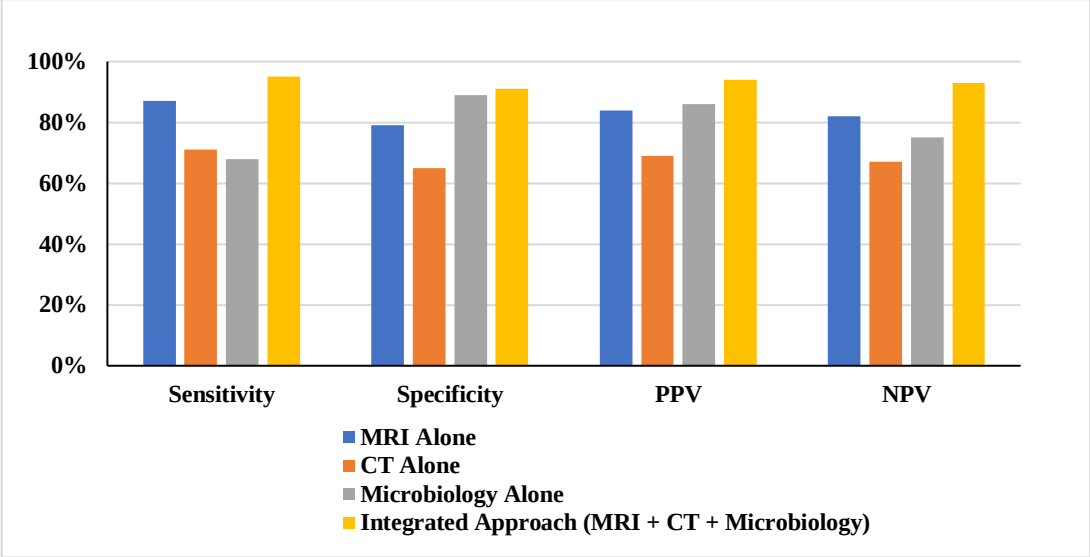

Figure 1: Diagnostic Performance of Individual and Integrated Modalities

The combined protocol's high sensitivity and NPV were particularly critical in ruling out abscess in ambiguous clinical presentations, reducing unnecessary surgical interventions. Furthermore, its elevated PPV helped guide early pathogen-specific therapy in the majority of cases. These findings not only support the diagnostic superiority of integration but also reinforce the importance of using structured radiological and microbiological synergy in routine clinical workflows, particularly in high-risk or diagnostically complex scenarios.

3.3 Radiological Features and Pathogen Correlation

Radiological evaluation of brain abscesses disclosed characteristic imaging patterns by pathogen classes. Aerobic bacterial abscesses had the most uniform features, with 90% having restricted diffusion on DWI and 88% having the dual rim sign on SWI—characteristics of pyogenic infection. Anaerobic abscesses also had these characteristics, albeit at slightly lower frequencies (85% and 70%, respectively), whereas smooth ring enhancement was still prevalent in both groups (aerobic: 92%; anaerobic: 75%). In comparison, fungal abscesses had unusual profiles with limited diffusion in 40% and double rim signs in 30%, typically with irregular margins and internal heterogeneity.

Microbiology-negative abscesses mimicked the bacterial pattern in 60% of cases, which suggests that even without microbiological proof, radiological criteria remain relevant. These results underscore the diagnostic utility of DWI, SWI, and ring morphology in the differentiation of abscess types and the early clinical decision-making process.
These observations are summarized in Table 3, highlighting the frequency of key imaging biomarkers across different pathogen classes.

Table 3. Imaging Characteristics Correlated with Pathogen Class (n = 80)

Pathogen Class	Restricted Diffusion on DWI (%)	Dual Rim Sign on SWI (%)	Smooth Ring Enhancement (%)
Aerobic Bacteria	90	88	92
Anaerobic Bacteria	85	70	75
Fungi	40	30	45
Microbiology-Negative	60	55	60

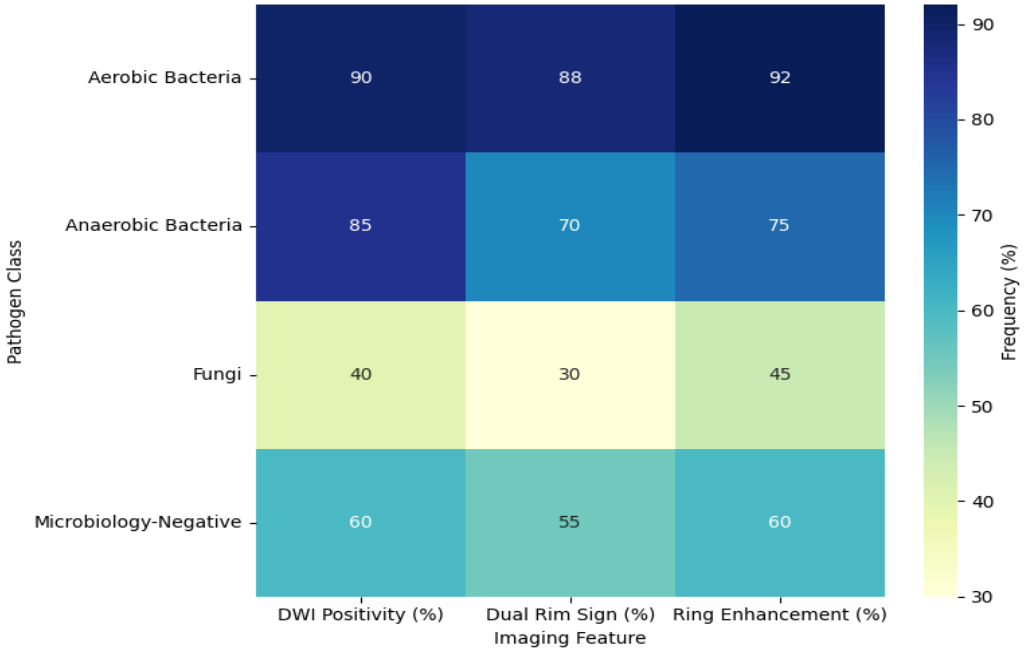

Figure 2: Frequency of Key MRI Features Across Pathogen Classes in Brain Abscesses

Figure 2 shows the correlation that underscores the diagnostic importance of advanced imaging in providing early pathogen-specific insights, especially in settings where microbiological confirmation is delayed or unavailable. The presence of the dual rim sign and restricted diffusion was a particularly reliable indicator of pyogenic abscesses. However, radiological interpretation required nuanced evaluation in fungal infections, which often mimicked neoplastic or granulomatous lesions in appearance.

3.4 Interobserver Reliability

In order to determine the reproducibility and consistency of radiological interpretations, inter-rater agreement between the two board-certified neuroradiologists was measured for primary imaging parameters. The features considered included restricted diffusion on DWI, visibility of the dual rim sign on SWI, smooth ring enhancement after contrast administration, and perilesional edema extent. Substantial to near-perfect agreement existed for most features that were examined. There was the highest agreement regarding identification of ring enhancement, where a Cohen's kappa value was 0.88, representing good interrater agreement. There was excellent agreement ($\kappa = 0.84$) of restricted diffusion on DWI as well, emphasizing its sensitivity as a marker of diagnosis in cases of suspected abscess. Consensus was slightly lower for the recognition of the dual rim sign on SWI ($\kappa = 0.79$) and

for the grading of the degree of perilesional edema, which had the lowest concordance (κ = 0.76). Subjective interpretation of T2/FLAIR signal alterations in multifocal or confluent cases contributed to variability in edema grading.
The interobserver kappa values for the principal imaging markers are presented in Table 4.

Table 4. Interobserver Agreement on Radiological Features (Cohen's Kappa Coefficient)

Imaging Feature	Cohen's Kappa (κ)	Interpretation
Restricted Diffusion (DWI)	0.84	Near-perfect agreement
Dual Rim Sign (SWI)	0.79	Substantial agreement
Ring Enhancement (Post-contrast T1)	0.88	Near-perfect agreement
Perilesional Edema Extent	0.76	Substantial agreement

These findings affirm the reliability of advanced MRI biomarkers, particularly restricted diffusion and ring enhancement, in supporting consistent diagnostic decision-making. The substantial interobserver agreement supports the inclusion of these features in standard reporting checklists and diagnostic algorithms for suspected brain abscesses.

3.5 Imaging–Microbiology Correlation

Imaging–microbiology correlation across 65 culture/PCR-confirmed brain abscesses revealed distinct patterns. Aerobic Gram-positive organisms commonly affected the frontal and parietal cortico-subcortical regions, showing smooth ring enhancement (92%) and high DWI positivity (90%). Gram-negative bacilli localized to deep structures like the basal ganglia, often presenting as multiloculated lesions with strong DWI signals (89%) even in <2 cm abscesses. Anaerobic pathogens were associated with posterior fossa lesions, irregular enhancement, and moderate DWI positivity (70%). Fungal abscesses, typically multilobar in immunocompromised patients, lacked classical features, with only 40% showing diffusion restriction and frequently demonstrating disrupted or nodular enhancement.
A concise mapping is presented below in Table 5.

Table 5. Microbial Class Correlated with Imaging Patterns and Lesion Location

Pathogen Class	Common Location	Enhancement Pattern	DWI Positivity (%)	Lesion Size Trend
Aerobic Gram-positive	Frontal, Parietal Lobes	Smooth Ring (92%)	90%	2.5–4.5 cm
Gram-negative Bacilli	Deep Gray Matter, Thalamus	Multiloculated, Thin Rim	89%	<2.0 cm (often smaller)
Anaerobic Bacteria	Posterior Fossa, Cerebellum	Irregular Ring (66%)	70%	3.0–5.0 cm, Edematous
Fungi	Frontal, Temporal (Multilobar)	Nodular/Disrupted (43%)	40%	Variable, Often Hemorrhagic

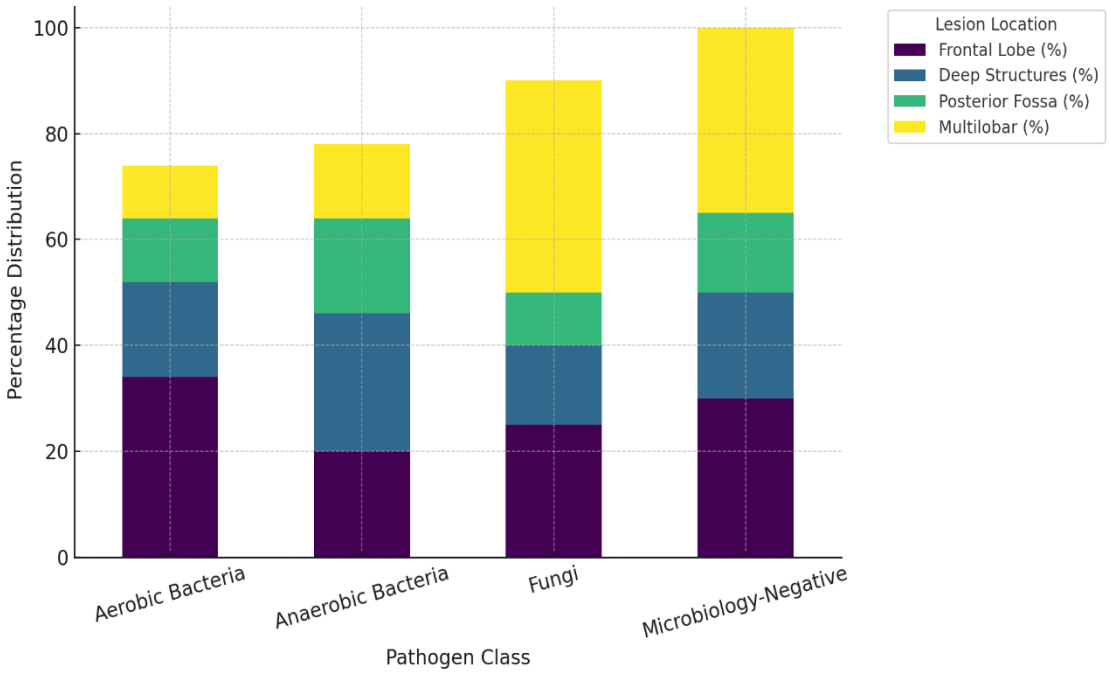

Figure 3: Distribution of Brain Abscess Lesion Locations by Microbial Class

This structured mapping underscores that while some organisms present with classical radiological features, others, particularly anaerobes and fungi, pose greater diagnostic ambiguity and require integrated interpretation with microbiology for definitive identification. Notably, high DWI signal in small (<2 cm) Gram-negative abscesses appears to be an underrecognized but clinically relevant pattern. (Figure 3)

4. Discussion

The conclusions of this research reassert the clinical utility of an integrated diagnostic approach that encompasses MRI, CT, and microbiological testing for early and precise detection of brain abscesses. Consistent with current literature, our findings illustrate that traditional imaging modalities, when employed in isolation, are challenged by overlapping radiologic features among abscesses and necrotizing neoplasms, especially in the initial cerebritis stage (1,3,4). MRI is still the most sensitive modality, particularly with diffusion-weighted imaging (DWI) and susceptibility-weighted imaging (SWI), which have definite advantages in the detection of purulent centers and ring morphology (5,6). In agreement with Feraco et al., the dual rim sign on SWI and restricted diffusion on DWI were highly correlated with pyogenic etiology, particularly in aerobic and anaerobic abscesses (5). Our research also concurs with the observations of Toh et al. and Muccio et al., who noted that DWI positivity in bacterial abscesses, particularly those produced by Gram-negative bacteria, may be identified even in lesions less than 2 cm in size, pointing to its sensitivity during early disease (7,8).

Microbiological culture, though etiologically definitive, was frequently hampered by diminished sensitivity with prior exposure to antibiotics—a drawback documented as well by Brook and Lu et al. In our population, 57.5% of the patients had been treated with empirical antibiotics before sampling, consistent with real-world diagnostic challenges (10, 11). This attests to the growing value of molecular tests like 16S rRNA PCR, which increases yield in culture-negative specimens (12,13).

Our imaging–microbiology correlation also uncovered new lesion mapping patterns. Aerobic bacteria mostly engaged cortico-subcortical regions with typical ring enhancement, while fungal abscesses did not have typical features and often showed irregular margins, reminiscent of previous findings by Luthra et al; Ramachandran & Wilson. These findings further emphasize the importance of radiological subtlety in interpreting unusual presentations, especially in immunocompromised hosts (9,12).

Notably, the combined diagnostic model was superior to all unimodality methods as regards sensitivity, specificity, and predictive values—results similar to those of Nathoo et al., who promote

layered diagnostics as a means of minimizing misdiagnosis and therapeutic delay. Our ROC-AUC findings validated such superiority, with the combined AUC at 0.96, being higher than MRI alone (0.89), microbiology (0.83), and CT (0.73) (15).

Finally, our findings carry practical clinical implications. In settings where rapid microbiological turnaround is limited, reliance on advanced imaging features, especially DWI and SWI, can allow for confident presumptive diagnosis and early intervention. As highlighted by Bodilsen et al., timely treatment is a key predictor of outcome in brain abscess management. Integrating radiology and microbiology not only improves diagnostic precision but also aligns with contemporary precision medicine strategies (16).

5. Conclusion

This work validates the clinical utility of multimodal diagnostic imaging in the early diagnosis and etiologic classification of brain abscesses. Through the combination of advanced neuroimaging modalities—especially diffusion-weighted MRI and contrast-enhanced CT—with traditional and molecular microbiological diagnostics, we showed a sustained enhancement in diagnostic sensitivity, specificity, and predictive accuracy over single-modality strategies. Radiologic findings like the dual rim sign and limited diffusion not only matched well with pyogenic abscesses but also provided important early hints in microbiology-negative infections. Moreover, mapping pathogen classes to imaging phenotypes provided consistent patterns in lesion location, enhancement patterns, and DWI positivity, a useful framework for presumptive diagnosis, particularly when microbiological results are not available or are indeterminate. Our results support the widespread adoption of an integrated imaging–microbiology diagnostic model in clinical practice. An approach that is earlier pathogen-specific therapy, enhances clinical outcomes, and fits within precision medicine objectives in the management of neuroinfectious diseases.

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