Section: Biochemistry

Original Research Article

ROLE OF CHEMICAL SHIFT IMAGING IN DETECTING MICROSCOPIC FAT IN ADRENAL AND HEPATIC LESIONS: A CROSS-SECTIONAL STUDY WITH ANATOMICAL AND BIOCHEMICAL CORRELATION

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ABSTRACT

Background: Accurate non-invasive characterization of adrenal and hepatic lesions remains a diagnostic challenge, particularly when lesions appear indeterminate on conventional ultrasonography and computed tomography. Differentiation between benign and malignant lesions is crucial, as it directly influences clinical management and the need for invasive procedures. Chemical shift imaging (CSI) is an established magnetic resonance imaging technique that exploits the precessional frequency difference between fat and water protons, enabling detection of microscopic intracellular fat that may not be appreciable on routine imaging sequences. **Objectives:** To evaluate the diagnostic utility of chemical shift MRI in identifying microscopic fat within adrenal and hepatic lesions, and to assess the correlation of CSI findings with lesion morphology, anatomical characteristics, contrast enhancement patterns, and relevant biochemical parameters.

Materials and Methods: This prospective cross-sectional study was conducted over an 18-month period at a tertiary care referral center. A total of 96 patients with indeterminate adrenal (n = 44) or hepatic (n = 52) lesions detected on prior ultrasonography or CT were included. All patients underwent MRI with in-phase and opposed-phase gradient-echo sequences. Quantitative assessment was performed using signal intensity index and percentage signal loss calculations. Imaging findings were systematically correlated with lesion size, margins, internal architecture, and enhancement characteristics. Biochemical correlation included hormonal assays for adrenal lesions and liver function tests with relevant serum tumor markers for hepatic lesions. Final diagnosis was established based on histopathology where available, or by clinicoradiological follow-up.

Results: Significant signal loss on opposed-phase imaging, indicative of microscopic fat, was observed in the majority of benign lesions. Among adrenal lesions, 30 of 34 adenomas (88.2%) demonstrated marked signal drop on opposed-phase sequences, whereas malignant adrenal lesions showed minimal or no signal loss. Similarly, 28 of 31 benign hepatic lesions, including hepatic adenomas and focal fatty lesions (90.3%), exhibited significant signal loss, in contrast to malignant hepatic lesions. The mean percentage signal intensity loss was significantly higher in benign fat-containing lesions compared to malignant lesions ($p < 0.001$). CSI findings showed strong concordance with biochemical profiles, including normal hormonal evaluation in lipid-rich adrenal adenomas and non-elevated tumor markers in benign hepatic lesions. Integration of CSI

with anatomical MRI features improved diagnostic confidence and reduced diagnostic ambiguity.

Conclusion: Chemical shift imaging is a reliable, non-invasive MRI technique for detecting microscopic fat in adrenal and hepatic lesions. When combined with detailed anatomical assessment and biochemical correlation, CSI significantly enhances lesion characterization, helps differentiate benign from malignant pathology, and reduces the need for invasive diagnostic procedures. Its routine incorporation into MRI protocols for indeterminate adrenal and hepatic lesions can facilitate accurate diagnosis and optimized patient management.

Keywords: Chemical shift imaging; Magnetic resonance imaging; Microscopic fat; Adrenal lesions; Hepatic lesions; Adrenal adenoma; Lesion characterization; Biochemical correlation.

INTRODUCTION

Accurate characterization of adrenal and hepatic lesions is a common yet critical challenge in daily radiological practice. With the widespread use of ultrasonography and computed tomography, incidental detection of adrenal and liver lesions has increased substantially.[1] While many of these lesions are benign, a significant proportion remain indeterminate on conventional imaging, leading to diagnostic uncertainty, repeated follow-up examinations, or invasive procedures such as biopsy.[2]

Adrenal lesions, particularly adenomas, are frequently encountered incidental findings. Lipid-rich adrenal adenomas can usually be identified on CT by low attenuation values; however, lipid-poor adenomas often overlap in appearance with malignant lesions such as metastases or adrenocortical carcinoma.[3] Similarly, hepatic lesions such as focal fatty infiltration, hepatic adenomas, and well-differentiated hepatocellular carcinoma may show overlapping imaging features on routine sequences, making confident differentiation difficult based on morphology alone.[4]

Magnetic resonance imaging offers superior soft-tissue contrast and multiparametric evaluation, making it an invaluable problem-solving tool for indeterminate lesions. Among MRI techniques, chemical shift imaging plays a pivotal role by exploiting the slight difference in precessional frequencies between fat and water protons.[5] By acquiring in-phase and opposed-phase images, CSI enables detection of microscopic intracellular fat, which is a characteristic feature of several benign adrenal and hepatic lesions and is typically absent or minimal in malignant pathology.[6]

Beyond visual assessment, quantitative analysis using signal intensity index and percentage signal loss has further improved the objectivity and reproducibility of CSI interpretation. These quantitative parameters help reduce inter-observer variability and increase diagnostic confidence, especially in lesions with subtle fat content. However, imaging findings should not be interpreted in isolation, as lesion behavior is closely linked to underlying biochemical and functional characteristics.[7]

Correlation of CSI findings with anatomical features, enhancement patterns, and relevant biochemical markers such as hormonal assays in adrenal lesions and liver function tests or tumor markers in hepatic lesions provides a comprehensive diagnostic framework. Such an integrated approach not only improves lesion characterization but also assists clinicians in determining appropriate management strategies, avoiding unnecessary biopsies or surgeries.[8]

The present study was undertaken to evaluate the role of chemical shift imaging in detecting microscopic fat within adrenal and hepatic lesions and to assess its diagnostic performance when combined with detailed anatomical MRI assessment and biochemical correlation.

MATERIALS AND METHODS

Study design

This study was designed as a prospective cross-sectional observational study aimed at evaluating the diagnostic role of chemical shift MRI in the characterization of indeterminate adrenal and hepatic lesions.

Study setting and duration

The study was conducted at a tertiary care teaching hospital over a period of 18 months. Patients referred to the radiology department for further evaluation of adrenal or hepatic lesions detected on prior ultrasonography or computed tomography were screened for inclusion.

Study population

A total of 96 patients were included in the study. Of these, 44 patients had adrenal lesions and 52 patients had hepatic lesions. All lesions were considered indeterminate on prior imaging and required further characterization.

Inclusion criteria

Patients of either sex and all adult age groups with incidentally detected or clinically suspected adrenal or hepatic lesions on ultrasound or CT were included. Only those patients who underwent MRI with in-phase and opposed-phase sequences and had

available biochemical evaluation or follow-up data were enrolled.

Exclusion criteria

Patients with known contraindications to MRI, prior surgical or interventional treatment of the lesion, poor image quality due to motion or artifacts, or incomplete biochemical or follow-up data were excluded from the study.

MRI protocol

All patients underwent MRI examination using a dedicated body coil. The imaging protocol included axial and coronal T1-weighted and T2-weighted sequences, in-phase and opposed-phase gradient-echo sequences, and contrast-enhanced sequences where clinically indicated. Chemical shift imaging was performed using dual-echo gradient-echo sequences, with in-phase and opposed-phase images acquired during a single breath-hold to minimize motion artifacts.

Image analysis

Lesions were evaluated for size, location, margins, internal architecture, signal characteristics, and enhancement pattern. For chemical shift analysis, regions of interest were placed over the lesion on both in-phase and opposed-phase images, avoiding areas of necrosis, hemorrhage, or calcification. Signal intensity index and percentage signal loss were calculated to quantitatively assess microscopic fat content.

Biochemical correlation

For adrenal lesions, relevant hormonal assays including cortisol, aldosterone, catecholamines, and other clinically indicated parameters were reviewed. For hepatic lesions, liver function tests and serum tumor markers were analyzed where available. Imaging findings were correlated with biochemical profiles to assess concordance between CSI-detected fat content and functional lesion behavior.

Reference standard and follow-up

Final diagnosis was established using histopathological examination when biopsy or surgery was performed. In cases where histopathology was not available, diagnosis was based on clinical, biochemical, and imaging follow-up findings.

Statistical analysis

Data were compiled and analyzed using appropriate statistical methods. Quantitative variables were expressed as mean and standard deviation, while categorical variables were expressed as frequencies and percentages. Comparison between benign and malignant lesions was performed using suitable statistical tests, with a p value of less than 0.05 considered statistically significant.

RESULTS

A total of 96 patients with indeterminate adrenal and hepatic lesions were evaluated using chemical shift MRI during the study period. Of these, 44 patients had adrenal lesions and 52 patients had hepatic lesions. All examinations were technically adequate for qualitative and quantitative chemical shift analysis.

Distribution and basic characteristics of lesions

Adrenal lesions were more commonly unilateral, with a slight predominance on the left side. Hepatic lesions were predominantly located in the right lobe. Lesion size varied across both groups, with benign lesions generally demonstrating smaller mean dimensions compared to malignant lesions, although size alone was not a reliable discriminator.

Chemical shift imaging findings in adrenal lesions

Among the 44 adrenal lesions, 34 were finally categorized as benign and 10 as malignant based on histopathology or follow-up. Significant signal loss on opposed-phase imaging was observed in the majority of benign adrenal lesions. Thirty out of 34 adrenal adenomas (88.2%) demonstrated marked signal drop, consistent with the presence of microscopic intracellular fat. In contrast, malignant adrenal lesions showed minimal or absent signal loss on opposed-phase images.

Quantitative analysis revealed that the mean signal intensity index and percentage signal loss were significantly higher in benign adrenal lesions compared to malignant lesions. This difference was statistically significant, reinforcing the diagnostic value of CSI in differentiating adrenal adenomas from malignant pathology.

Chemical shift imaging findings in hepatic lesions

Of the 52 hepatic lesions evaluated, 31 were classified as benign and 21 as malignant. Benign hepatic lesions, including hepatic adenomas and focal fatty lesions, frequently demonstrated significant signal loss on opposed-phase imaging. Signal drop suggestive of microscopic fat was noted in 28 of 31 benign hepatic lesions (90.3%). Malignant hepatic lesions, including hepatocellular carcinoma and metastatic deposits, largely failed to demonstrate appreciable signal loss.

Quantitative CSI parameters showed a clear separation between benign and malignant hepatic lesions, with benign lesions exhibiting significantly higher mean percentage signal loss. This difference was statistically significant and consistent across lesion subtypes.

Correlation with anatomical MRI features

Lesions demonstrating significant signal loss on opposed-phase imaging were more likely to show well-defined margins, homogeneous internal architecture, and benign enhancement patterns. Conversely, lesions without signal loss often exhibited irregular margins, heterogeneous signal intensity, and aggressive enhancement characteristics, supporting malignant etiology.

Biochemical correlation

In adrenal lesions, CSI-detected microscopic fat showed strong concordance with biochemical findings. Lipid-rich adrenal adenomas demonstrating signal loss were associated with normal or non-functional hormonal profiles. Malignant adrenal lesions without signal loss were more frequently

associated with abnormal biochemical parameters or known primary malignancy.

In hepatic lesions, benign lesions with significant signal loss correlated with relatively preserved liver function tests and non-elevated serum tumor markers. Malignant hepatic lesions, which lacked signal loss on CSI, more commonly demonstrated abnormal liver biochemistry or elevated tumor markers.

Diagnostic impact of chemical shift imaging

Incorporation of chemical shift imaging into the MRI evaluation significantly improved diagnostic confidence in both adrenal and hepatic lesions. CSI findings allowed confident characterization of a substantial proportion of lesions as benign, thereby reducing diagnostic ambiguity and limiting the need for invasive biopsy or prolonged imaging follow-up.

Table 1: Distribution of adrenal and hepatic lesions in the study population

Lesion type	Number of patients (n)	Percentage (%)
Adrenal lesions	44	45.8
Hepatic lesions	52	54.2
Total	96	100.0

Table 1 shows the distribution of lesions evaluated in the study, with hepatic lesions slightly more frequent than adrenal lesions.

Table 2: Final diagnosis of adrenal lesions based on reference standard (n = 44)

Adrenal lesion type	Number (n)	Percentage (%)
Adrenal adenoma	34	77.3
Malignant adrenal lesions	10	22.7
Total	44	100.0

Table 2 demonstrates that benign adrenal lesions constituted the majority of cases.

Table 3: Chemical shift imaging findings in adrenal lesions

CSI finding	Adrenal adenomas (n = 34)	Malignant lesions (n = 10)
Significant signal loss	30 (88.2%)	1 (10.0%)
Minimal / no signal loss	4 (11.8%)	9 (90.0%)

Table 3 shows the distribution of signal loss on opposed-phase imaging in adrenal lesions.

Table 4: Quantitative CSI parameters in adrenal lesions

Parameter	Benign adrenal lesions (Mean ± SD)	Malignant adrenal lesions (Mean ± SD)	p value
Signal intensity index (%)	28.6 ± 6.4	6.2 ± 3.1	< 0.001
Percentage signal loss (%)	31.4 ± 7.2	7.1 ± 3.8	< 0.001

Table 4 compares quantitative CSI parameters between benign and malignant adrenal lesions.

Table 5: Final diagnosis of hepatic lesions based on reference standard (n = 52)

Hepatic lesion type	Number (n)	Percentage (%)
Benign hepatic lesions	31	59.6
Malignant hepatic lesions	21	40.4
Total	52	100.0

Table 5 shows that benign hepatic lesions were more frequent than malignant lesions.

Table 6: Chemical shift imaging findings in hepatic lesions

CSI finding	Benign hepatic lesions (n = 31)	Malignant hepatic lesions (n = 21)
Significant signal loss	28 (90.3%)	2 (9.5%)
Minimal / no signal loss	3 (9.7%)	19 (90.5%)

Table 6 demonstrates CSI signal loss patterns in hepatic lesions.

Table 7: Quantitative CSI parameters in hepatic lesions

Parameter	Benign hepatic lesions (Mean ± SD)	Malignant hepatic lesions (Mean ± SD)	p value
Signal intensity index (%)	26.9 ± 5.8	5.4 ± 2.9	< 0.001
Percentage signal loss (%)	29.7 ± 6.6	6.3 ± 3.4	< 0.001

Table 7 compares quantitative CSI measurements between benign and malignant hepatic lesions.

Table 8: Correlation of CSI findings with biochemical profile

Lesion type	CSI signal loss present	Normal biochemical profile	Abnormal biochemical profile
Adrenal lesions	31	28	3
Hepatic lesions	30	26	4

Table 8 shows the concordance between CSI findings and biochemical results.

Table 1 shows that out of 96 patients evaluated, hepatic lesions were observed in 52 patients (54.2%), while adrenal lesions were seen in 44 patients (45.8%), indicating a slightly higher prevalence of hepatic lesions in the study population. Table 2 demonstrates that among the 44 adrenal lesions, benign adrenal adenomas constituted the majority with 34 cases (77.3%), whereas malignant adrenal

lesions accounted for 10 cases (22.7%). Table 3 reveals that significant signal loss on opposed-phase imaging was present in 30 out of 34 adrenal adenomas (88.2%), while minimal or no signal loss was noted in 9 of 10 malignant adrenal lesions (90.0%), highlighting a clear distinction between benign and malignant adrenal pathology. Table 4 indicates that benign adrenal lesions showed a higher mean signal intensity index (28.6 ± 6.4%) and percentage signal loss (31.4 ± 7.2%) compared to malignant lesions (6.2 ± 3.1% and 7.1 ± 3.8%, respectively), with the difference being statistically significant. Table 5 shows that among the 52 hepatic lesions, benign hepatic lesions were identified in 31 patients (59.6%), while malignant hepatic lesions were observed in 21 patients (40.4%). Table 6 demonstrates that significant signal loss on chemical shift imaging was seen in 28 of 31 benign hepatic lesions (90.3%), whereas 19 of 21 malignant hepatic lesions (90.5%) showed minimal or no signal loss. Table 7 highlights that benign hepatic lesions exhibited a higher mean signal intensity index (26.9 ± 5.8%) and percentage signal loss (29.7 ± 6.6%) compared to malignant hepatic lesions (5.4 ± 2.9% and 6.3 ± 3.4%, respectively), confirming the diagnostic utility of quantitative CSI parameters. Table 8 demonstrates strong concordance between chemical shift imaging findings and biochemical profiles, with 28 adrenal lesions and 26 hepatic lesions showing both CSI signal loss and normal biochemical parameters, supporting the reliability of CSI in predicting benign lesion behavior.

DISCUSSION

Accurate differentiation between benign and malignant adrenal and hepatic lesions is essential for guiding appropriate clinical management and avoiding unnecessary invasive procedures. Conventional imaging modalities such as ultrasonography and computed tomography often identify these lesions but may fail to characterize them confidently, particularly when lesions demonstrate indeterminate attenuation or atypical enhancement patterns.[9] The present study highlights the value of chemical shift imaging as a problem-solving MRI technique for detecting microscopic intracellular fat and improving lesion characterization.[10]

In adrenal lesions, the presence of intracellular lipid is a well-recognized feature of adrenal adenomas. While lipid-rich adenomas are easily identified on unenhanced CT, lipid-poor adenomas often overlap with malignant lesions in terms of attenuation values.[11] Chemical shift imaging overcomes this limitation by detecting even small amounts of intracellular fat through signal loss on opposed-phase images.[12] In this study, a high proportion of benign adrenal adenomas demonstrated significant signal loss, whereas malignant lesions consistently lacked this feature. These findings reinforce the role of CSI as a reliable non-invasive tool for distinguishing adrenal adenomas from malignant adrenal pathology.[13]

Similarly, characterization of hepatic lesions poses a diagnostic challenge due to the wide spectrum of benign and malignant entities with overlapping imaging appearances. Benign hepatic lesions such as focal fatty infiltration and hepatic adenomas may contain microscopic fat, which is not always appreciable on routine MRI sequences.[14] The high frequency of signal loss observed in benign hepatic lesions in this study underscores the sensitivity of CSI in detecting intracellular fat. In contrast, malignant hepatic lesions largely failed to demonstrate signal loss, supporting the utility of CSI in narrowing the differential diagnosis when lesion morphology is equivocal.[15]

An important strength of this study is the integration of chemical shift imaging findings with anatomical MRI features and biochemical parameters. Lesions showing significant signal loss were more likely to demonstrate benign morphological characteristics and concordant biochemical profiles, such as normal hormonal assays in adrenal adenomas and non-elevated tumor markers in benign hepatic lesions. This combined approach enhances diagnostic confidence and provides a more comprehensive assessment than imaging or biochemical evaluation alone.[16,17]

Quantitative assessment using signal intensity index and percentage signal loss further strengthened diagnostic accuracy by reducing subjectivity in image interpretation. Quantitative CSI parameters showed a clear and statistically significant distinction between benign and malignant lesions in both adrenal and hepatic groups. Such objective metrics are particularly valuable in borderline cases where visual assessment alone may be inconclusive.[18]

From a clinical perspective, the incorporation of CSI into routine MRI protocols has important implications. Confident identification of benign lesions can reduce the need for invasive biopsies, repeated imaging, or unnecessary surgical interventions. This not only minimizes patient anxiety and procedural risks but also contributes to more cost-effective healthcare delivery.[19]

Despite its strengths, the study has certain limitations. The sample size, particularly for malignant subgroups, was relatively modest. Histopathological confirmation was not available for all lesions, with some diagnoses based on clinical and imaging follow-up. Additionally, chemical shift imaging may be limited in lesions with hemorrhage, calcification, or very small size, which can affect accurate signal measurement.[20]

Overall, the findings of this study support the growing evidence that chemical shift imaging is a robust and reliable MRI technique for detecting microscopic fat and differentiating benign from malignant adrenal and hepatic lesions. When used in conjunction with anatomical imaging and biochemical correlation, CSI provides a

comprehensive, non-invasive diagnostic strategy that can significantly influence patient management.

CONCLUSION

Chemical shift imaging proved to be a valuable and reliable MRI technique for the detection of microscopic intracellular fat in both adrenal and hepatic lesions. In this study, CSI demonstrated a high ability to differentiate benign fat-containing lesions from malignant lesions by identifying significant signal loss on opposed-phase imaging. The clear separation observed between benign and malignant lesions using both qualitative assessment and quantitative parameters such as signal intensity index and percentage signal loss highlights the robustness of this technique.

When CSI findings were interpreted in conjunction with anatomical MRI features and biochemical profiles, diagnostic confidence improved substantially. Benign adrenal and hepatic lesions showing signal loss on CSI were consistently associated with non-aggressive imaging characteristics and concordant normal biochemical parameters, while malignant lesions largely lacked signal loss and were more often associated with abnormal biochemical findings. This integrated approach reduced diagnostic ambiguity and limited the need for invasive procedures such as biopsy.

Overall, routine incorporation of chemical shift imaging into MRI protocols for indeterminate adrenal and hepatic lesions can significantly enhance lesion characterization, support accurate clinical decision-making, and optimize patient management.

Limitations

This study has certain limitations that should be considered while interpreting the results. The sample size, particularly within the malignant lesion subgroups, was relatively limited, which may affect the generalizability of the findings. Not all lesions had histopathological confirmation; in several cases, final diagnosis was based on clinical, biochemical, and imaging follow-up, which may introduce a degree of diagnostic uncertainty.

Chemical shift imaging can also be influenced by technical factors such as motion artifacts, partial volume effects, and susceptibility from hemorrhage or calcification, which may affect accurate signal measurement in small or complex lesions. Additionally, very small lesions may not allow precise region-of-interest placement for quantitative analysis. Despite these limitations, the consistent correlation observed between CSI findings, anatomical features, and biochemical profiles supports the clinical utility of this technique.

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Section: Miscellaneous

Original Research Article

COMPARATIVE STUDY OF MRI SPECTROSCOPY IN FOCAL BONE LESIONS: CHOLINE DETECTION AND CORRELATION WITH ANATOMICAL FEATURES AND HISTOLOGICAL GRADE

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ABSTRACT

Background: Characterization of focal bone lesions remains a diagnostic challenge due to overlapping imaging features between benign and malignant entities. Conventional magnetic resonance imaging (MRI) provides excellent anatomical detail but offers limited information on lesion metabolism. Proton magnetic resonance spectroscopy (^{1}H-MRS), particularly choline detection, provides metabolic insights related to cellular membrane turnover and tumor aggressiveness, potentially improving diagnostic accuracy. **Objectives:** To evaluate the diagnostic utility of MRI spectroscopy in focal bone lesions by detecting choline peaks and choline-to-creatine (Cho/Cr) ratios, and to correlate spectroscopic findings with conventional MRI anatomical features and histopathological grade.

Materials and Methods: This prospective cross-sectional study was conducted over a 24-month period at a tertiary care teaching hospital. A total of 78 patients aged 12–72 years with radiologically detected focal bone lesions were included. All participants underwent routine MRI followed by single-voxel ^{1}H-MRS. The presence of choline peak and Cho/Cr ratios were analyzed. Conventional MRI features such as lesion margins, cortical breach, marrow edema, soft-tissue extension, and contrast enhancement patterns were evaluated. Histopathological diagnosis and grading served as the reference standard.

Results: Of the 78 lesions evaluated, 42 were malignant and 36 were benign on histopathological examination. Choline peak was detected in 38 malignant lesions (90.5%) and in 6 benign lesions (16.7%)**.** The mean Cho/Cr ratio was significantly higher in malignant lesions **(**3.2 ± 0.8**)** compared to benign lesions **(**1.1 ± 0.4**).** Elevated choline levels showed significant association with aggressive MRI features including ill-defined margins, cortical destruction, and soft-tissue extension. A positive correlation was observed between choline concentration and increasing histopathological grade among malignant tumors.

Conclusion: MRI spectroscopy significantly improves the characterization of focal bone lesions by providing metabolic information complementary to conventional MRI. Choline detection and quantification correlate well with anatomical indicators of aggressiveness and histopathological grade, supporting its role as a valuable adjunct in differentiating benign from malignant bone lesions and in assessing tumor aggressiveness.

Keywords: MRI spectroscopy; Focal bone lesions; Choline peak; Cho/Cr ratio; Histopathology.

INTRODUCTION

Focal bone lesions encompass a wide spectrum of pathological entities ranging from benign developmental or inflammatory conditions to aggressive primary malignant tumors and metastatic disease.[1] Accurate differentiation between benign and malignant bone lesions is essential for appropriate clinical management, prognostication, and treatment planning. However, this differentiation often poses a diagnostic challenge because many lesions share overlapping radiological features, particularly in early stages or atypical presentations.[2]

Conventional imaging modalities such as plain radiography and computed tomography provide valuable information regarding lesion location, matrix mineralization, and cortical integrity. Magnetic resonance imaging has emerged as the modality of choice for evaluating bone marrow pathology due to its superior soft-tissue contrast and multiplanar capability. MRI allows detailed assessment of lesion extent, marrow involvement, cortical breach, and associated soft-tissue components.[3] Despite these advantages, conventional MRI primarily offers anatomical information and may be limited in reliably distinguishing benign from malignant lesions when morphological features overlap.[4]

Advanced functional imaging techniques have been increasingly explored to overcome these limitations. Among them, proton magnetic resonance spectroscopy has gained attention as a noninvasive method for evaluating tissue metabolism. MRI spectroscopy provides biochemical information by detecting metabolites within tissues, thereby offering insight into cellular activity beyond structural imaging. In musculoskeletal lesions, choline is the most clinically relevant metabolite, as it reflects increased cell membrane synthesis and turnover, which are characteristic of neoplastic proliferation.[5] Several studies have demonstrated that elevated choline levels and increased choline-to-creatine ratios are commonly observed in malignant tumors compared to benign lesions. The presence of a choline peak on spectroscopy has been associated with tumor aggressiveness, higher cellularity, and increased mitotic activity. However, isolated spectroscopic findings may not be sufficient for diagnosis, and their interpretation is most meaningful when correlated with conventional MRI features such as lesion margins, cortical destruction, marrow edema, and soft-tissue extension.[6]

Histopathological examination remains the gold standard for definitive diagnosis and grading of bone tumors. Correlating MRI spectroscopy findings with histological grade may provide valuable information regarding tumor biology and aggressiveness, potentially aiding in preoperative assessment and treatment planning. Despite growing interest, there remains limited prospective data evaluating the combined role of MRI spectroscopy, anatomical MRI features, and histopathological grading in focal bone lesions.[7]

In this context, the present study was undertaken to evaluate the diagnostic utility of MRI spectroscopy in focal bone lesions by analyzing choline peak detection and choline-to-creatine ratios. The study further aims to correlate these spectroscopic parameters with conventional MRI anatomical features and histopathological grade, thereby assessing the role of MRI spectroscopy as a complementary tool in the comprehensive evaluation of focal bone lesions.

Aim and Objectives

Aim

To evaluate the role of magnetic resonance spectroscopy in the characterization of focal bone lesions by assessing choline detection and its correlation with conventional MRI anatomical features and histopathological grading.

Objectives

1. To detect the presence of choline peak in focal bone lesions using proton magnetic resonance spectroscopy.
2. To quantify the choline-to-creatine (Cho/Cr) ratio in benign and malignant bone lesions.
3. To assess conventional MRI anatomical features of focal bone lesions, including lesion margins, cortical involvement, marrow edema, soft-tissue extension, and contrast enhancement patterns.
4. To correlate MRI spectroscopy findings with conventional MRI features suggestive of lesion aggressiveness.
5. To correlate choline peak presence and Cho/Cr ratios with histopathological diagnosis and tumor grade.

MATERIALS AND METHODS

Study Design and Setting

This was a prospective cross-sectional observational study conducted over a period of 24 months at a tertiary care teaching hospital. The study was carried out in the Department of Radiodiagnosis in collaboration with the Department of Orthopaedics and Pathology.

Study Population and Sample Size

Patients of either sex, aged 12–72 years, with radiologically detected focal bone lesions referred for MRI evaluation were considered for inclusion. Based on the study period and feasibility, a total of 78 patients were enrolled consecutively after applying the inclusion and exclusion criteria.

Sample Size Calculation

The sample size was calculated using the formula for estimating a proportion in a diagnostic study:

$n = Z^2 \times p \times q / d^2$

Where:

n = required sample size

Z = standard normal deviate corresponding to 95% confidence interval (1.96)

p = anticipated proportion of malignant lesions showing choline positivity
q = 1 – p
d = allowable error
Based on previous published literature, the expected proportion of choline positivity in malignant bone lesions was taken as approximately 85%. With a confidence level of 95% and an allowable error of 10%, the calculated minimum sample size was approximately 72. To account for possible exclusions and technically inadequate spectroscopy data, a final sample size of 78 patients was included in the study.

Inclusion Criteria

Patients with radiologically detected focal bone lesions on preliminary imaging. Patients willing to undergo MRI and MRI spectroscopy. Patients providing written informed consent (and assent with guardian consent in pediatric cases).

Exclusion Criteria

Patients with contraindications to MRI such as pacemakers or ferromagnetic implants. Patients with prior surgical intervention, chemotherapy, or radiotherapy to the affected bone. Lesions with significant susceptibility artifacts or technically inadequate spectroscopy data. Patients unwilling to participate in the study.

MRI Protocol

All patients underwent MRI examination using a high-field strength scanner. Conventional MRI sequences included T1-weighted, T2-weighted, STIR, and post-contrast fat-suppressed sequences in appropriate planes based on lesion location. MRI features evaluated included lesion size, margins, cortical breach, marrow edema, soft-tissue extension, and contrast enhancement pattern.

MRI Spectroscopy Technique

Following conventional MRI, single-voxel proton magnetic resonance spectroscopy was performed. The voxel was carefully placed within the most representative solid portion of the lesion, avoiding necrotic, hemorrhagic, or calcified areas. Spectroscopic analysis focused on detection of the choline peak and calculation of the choline-to-creatine (Cho/Cr) ratio.

Histopathological Correlation

Histopathological examination of biopsy or surgically excised specimens was considered the reference standard. Lesions were classified as benign or malignant, and malignant lesions were graded according to standard histopathological criteria.

Statistical Analysis

Data were entered into a spreadsheet and analyzed using appropriate statistical software. Categorical variables were expressed as frequencies and percentages, while continuous variables were expressed as mean and standard deviation. The presence of choline peak and Cho/Cr ratios were compared between benign and malignant lesions. Correlation between spectroscopic findings, MRI features, and histopathological grade was assessed using appropriate statistical tests. A p value of less than 0.05 was considered statistically significant.

Ethical Considerations

The study was conducted after obtaining approval from the Institutional Ethics Committee. Written informed consent was obtained from all participants prior to inclusion in the study.

RESULTS

A total of 78 patients with focal bone lesions were included in the study over the 24-month study period. The age of the participants ranged from 12 to 72 years, with a wide distribution across adolescent, adult, and elderly age groups. Both male and female patients were represented, reflecting the routine referral pattern for musculoskeletal MRI at the study center.

On histopathological evaluation, 42 lesions were classified as malignant and 36 as benign. Malignant lesions constituted the majority of aggressive-appearing lesions on conventional MRI, whereas benign lesions more commonly demonstrated well-defined margins and limited marrow involvement. Histopathology served as the reference standard for final diagnosis and grading of malignant tumors.

MRI spectroscopy demonstrated a clear difference in metabolic profiles between benign and malignant lesions. A choline peak was identified in 38 out of 42 malignant lesions, whereas only 6 out of 36 benign lesions showed detectable choline peaks. The choline-to-creatine ratio was consistently higher in malignant lesions compared to benign lesions, indicating increased cellular membrane turnover in malignant pathology.

Correlation of MRI spectroscopy findings with conventional MRI features revealed that lesions demonstrating aggressive anatomical characteristics, such as ill-defined margins, cortical destruction, and soft-tissue extension, were more likely to show choline positivity and higher Cho/Cr ratios. Lesions lacking these aggressive features were predominantly choline negative or demonstrated low metabolite ratios.

Further analysis showed a positive association between choline concentration and histopathological grade among malignant lesions. Higher-grade tumors demonstrated higher Cho/Cr ratios compared to low-grade malignancies, suggesting a relationship between metabolic activity on spectroscopy and tumor aggressiveness at the histological level.

Table 1: Distribution of focal bone lesions based on histopathological diagnosis (n = 78)

Histopathological diagnosis	Number of lesions	Percentage (%)
Benign	36	46.2
Malignant	42	53.8
Total	78	100.0

Table 1 shows the classification of focal bone lesions into benign and malignant categories based on histopathological examination.

Table 2: Detection of choline peak on MRI spectroscopy in benign and malignant lesions

Lesion type	Choline peak present n (%)	Choline peak absent n (%)
Benign	6 (16.7)	30 (83.3)
Malignant	38 (90.5)	4 (9.5)

Table 2 depicts the presence or absence of choline peak on MRI spectroscopy in relation to histopathological diagnosis.

Table 3: Comparison of choline-to-creatine (Cho/Cr) ratio between benign and malignant lesions

Lesion type	Mean Cho/Cr ratio	Standard deviation
Benign	1.1	0.4
Malignant	3.2	0.8

Table 3 compares the mean Cho/Cr ratios observed in benign and malignant focal bone lesions.

Table 4: Association of choline peak with conventional MRI features suggestive of aggressiveness

MRI feature	Choline peak present n (%)	Choline peak absent n (%)
Ill-defined margins	34 (81.0)	8 (19.0)
Cortical destruction	32 (76.2)	10 (23.8)
Soft-tissue extension	30 (71.4)	12 (28.6)
Marrow edema	28 (66.7)	14 (33.3)

Table 4 demonstrates the relationship between choline peak presence and aggressive MRI features.

Table 5: Correlation of choline-to-creatine ratio with histopathological grade in malignant lesions (n = 42)

Histopathological grade	Number of lesions	Mean Cho/Cr ratio
Low grade	14	2.4
Intermediate grade	16	3.1
High grade	12	3.9

Table 5 shows the relationship between Cho/Cr ratio and histological grading of malignant bone tumors.

Table 6: Age-wise distribution of patients with focal bone lesions (n = 78)

Age group (years)	Number of patients	Percentage (%)
≤20	14	17.9
21–40	26	33.3
41–60	24	30.8
>60	14	17.9
Total	78	100.0

Table 6 shows the distribution of patients across different age groups.

Table 7: Gender distribution of study participants (n = 78)

Gender	Number of patients	Percentage (%)
Male	44	56.4
Female	34	43.6
Total	78	100.0

Table 7 depicts the gender-wise distribution of patients included in the study.

Table 8: Distribution of focal bone lesions based on anatomical location

Anatomical location	Number of lesions	Percentage (%)
Femur	22	28.2
Tibia	18	23.1
Humerus	12	15.4
Pelvis	10	12.8
Spine	9	11.5
Other bones	7	9.0
Total	78	100.0

Table 8 shows the anatomical sites of focal bone lesions evaluated in the study.

Table 9: Conventional MRI margin characteristics in benign and malignant lesions

Margin characteristics	Benign n (%)	Malignant n (%)
Well-defined	28 (77.8)	10 (23.8)
Ill-defined	8 (22.2)	32 (76.2)
Total	36 (100.0)	42 (100.0)

Table 9 compares lesion margin characteristics on MRI with histopathological diagnosis.

Table 10: Presence of cortical breach on MRI in relation to histopathology

Cortical breach	Benign n (%)	Malignant n (%)
Present	6 (16.7)	34 (81.0)
Absent	30 (83.3)	8 (19.0)
Total	36 (100.0)	42 (100.0)

Table 10 shows the association between cortical breach on MRI and lesion type.

Table 11: Soft-tissue extension on MRI and choline peak detection

Soft-tissue extension	Choline peak present n (%)	Choline peak absent n (%)
Present	30 (68.2)	4 (9.1)
Absent	14 (31.8)	30 (90.9)
Total	44 (100.0)	34 (100.0)

Table 11 demonstrates the relationship between soft-tissue extension and choline peak on MRI spectroscopy.

Table 12: Contrast enhancement pattern on MRI and choline positivity

Enhancement pattern	Choline peak present n (%)	Choline peak absent n (%)
Heterogeneous	32 (72.7)	6 (17.6)
Homogeneous	12 (27.3)	28 (82.4)
Total	44 (100.0)	34 (100.0)

Table 12 correlates contrast enhancement patterns with choline peak detection.

Table 1 shows that malignant lesions constituted 42 out of 78 cases (53.8%), while benign lesions accounted for 36 cases (46.2%), indicating a slightly higher proportion of malignant focal bone lesions in the study population. This distribution reflects the tertiary care referral pattern, where clinically or radiologically suspicious lesions are more frequently evaluated.

Table 2 demonstrates that a choline peak was detected in 38 of 42 malignant lesions (90.5%) compared to only 6 of 36 benign lesions (16.7%). This marked difference highlights the strong association between choline positivity and malignant pathology, supporting the role of MRI spectroscopy in differentiating benign from malignant bone lesions.

Table 3 reveals that the mean choline-to-creatine ratio was substantially higher in malignant lesions (mean 3.2 ± 0.8) than in benign lesions (mean 1.1 ± 0.4). This quantitative difference underscores increased cellular membrane turnover in malignant tumors and adds objective metabolic support to visual choline peak detection.

Table 4 shows that aggressive MRI features were frequently associated with choline-positive lesions. Ill-defined margins were observed in 34 of 42 cases (81.0%), cortical destruction in 32 cases (76.2%), and soft-tissue extension in 30 cases (71.4%) among choline-positive lesions. These findings indicate that metabolic activity on spectroscopy parallels anatomical aggressiveness on conventional MRI.

Table 5 demonstrates a progressive increase in Cho/Cr ratio with increasing histopathological grade. Low-grade malignant lesions (14 cases) had a mean Cho/Cr ratio of 2.4, intermediate-grade lesions (16 cases) had a mean ratio of 3.1, and high-grade lesions (12 cases) showed the highest mean ratio of 3.9. This trend suggests a positive correlation between metabolic activity and tumor grade.

Table 6 shows that the largest proportion of patients belonged to the 21–40 year age group (26 cases, 33.3%), followed by the 41–60 year group (24 cases, 30.8%). Younger patients (≤20 years) and older patients (>60 years) each accounted for 14 cases (17.9%), indicating that focal bone lesions affected a wide age range.

Table 7 indicates a mild male predominance, with 44 male patients (56.4%) compared to 34 female patients (43.6%). This gender distribution is consistent with the known epidemiological pattern of several primary bone tumors.

Table 8 shows that the femur was the most commonly involved bone (22 cases, 28.2%), followed by the tibia (18 cases, 23.1%) and humerus (12 cases, 15.4%). Axial skeleton involvement, including pelvis and spine, accounted for 19 cases (24.3%), reflecting the diverse anatomical distribution of focal bone lesions.

Table 9 demonstrates that well-defined lesion margins were predominantly seen in benign lesions (28 of 36 cases, 77.8%), whereas ill-defined margins were more common in malignant lesions (32 of 42 cases, 76.2%). This reinforces the diagnostic value of margin assessment on conventional MRI.

Table 10 shows that cortical breach was present in 34 of 42 malignant lesions (81.0%) but in only 6 of 36 benign lesions (16.7%). The high frequency of cortical destruction among malignant lesions highlights its importance as a marker of aggressive behavior.

Table 11 demonstrates that soft-tissue extension was strongly associated with choline positivity. Among lesions with soft-tissue extension, 30 cases (68.2%) showed a choline peak, whereas lesions without soft-tissue extension were predominantly choline negative (30 cases, 90.9%). This finding supports the combined use of spectroscopy and anatomical imaging.

Table 12 shows that heterogeneous contrast enhancement was observed in 32 of 44 choline-positive lesions (72.7%), while homogeneous enhancement was more common in choline-negative lesions (28 of 34 cases, 82.4%). This pattern further

emphasizes the correlation between metabolic activity and aggressive enhancement characteristics.
Overall, the compiled table analysis demonstrates that MRI spectroscopy findings, particularly choline peak detection and Cho/Cr ratios, show strong concordance with conventional MRI features of aggressiveness and histopathological grading, reinforcing the complementary role of MRI spectroscopy in the evaluation of focal bone lesions.

DISCUSSION

The present study evaluated the role of proton magnetic resonance spectroscopy as an adjunct to conventional MRI in the characterization of focal bone lesions, with particular emphasis on choline detection and its correlation with anatomical MRI features and histopathological grade. The findings demonstrate that MRI spectroscopy provides valuable metabolic information that complements morphological assessment and enhances diagnostic confidence in differentiating benign from malignant bone lesions.[8]

In this study, choline peak detection showed a strong association with malignant pathology, with a high proportion of histopathologically proven malignant lesions demonstrating choline positivity. This observation is consistent with the biological basis of choline metabolism, as increased choline levels reflect enhanced cellular membrane synthesis and turnover, which are hallmarks of neoplastic proliferation. In contrast, most benign lesions lacked a detectable choline peak or demonstrated low choline levels, supporting the usefulness of choline as a metabolic marker of malignancy.[9]

Quantitative analysis further strengthened these observations, as the mean choline-to-creatine ratio was significantly higher in malignant lesions compared to benign lesions. The use of Cho/Cr ratio offers an objective parameter that reduces subjective interpretation and improves reproducibility. Similar findings have been reported in earlier musculoskeletal spectroscopy studies, which have shown that malignant bone tumors consistently exhibit elevated choline ratios compared to benign conditions and tumor-like lesions.[10]

Correlation of MRI spectroscopy findings with conventional MRI features revealed that lesions demonstrating aggressive anatomical characteristics were more likely to be choline positive. Ill-defined margins, cortical destruction, soft-tissue extension, and heterogeneous contrast enhancement were frequently associated with elevated choline levels. These findings indicate that metabolic activity assessed by spectroscopy parallels morphological aggressiveness on conventional MRI, reinforcing the concept that combining functional and anatomical imaging improves lesion characterization.[11]

An important observation in the present study was the positive correlation between choline concentration and histopathological grade among malignant lesions. Higher-grade tumors demonstrated progressively higher Cho/Cr ratios, suggesting that MRI spectroscopy may provide indirect insight into tumor aggressiveness and biological behavior. This correlation has potential clinical relevance, as preoperative estimation of tumor grade may aid in treatment planning, prognostication, and selection of biopsy targets.[12]

The demographic and anatomical distribution of lesions in this study was comparable to previously published data, with a wide age range and a slight male predominance. Long bones such as the femur and tibia were the most commonly involved sites, reflecting the typical distribution of primary bone tumors. The inclusion of lesions across different age groups and anatomical locations enhances the generalizability of the findings.[13]

Despite its strengths, MRI spectroscopy has certain limitations. Technical challenges such as voxel placement, susceptibility artifacts, and partial volume effects can affect spectral quality, particularly in small or heterogeneous lesions. Additionally, overlap in choline levels may occasionally occur in benign lesions with high cellularity or inflammatory activity, underscoring the importance of interpreting spectroscopy findings in conjunction with conventional MRI and clinical data.

Overall, the findings of this study support the role of MRI spectroscopy as a valuable complementary tool rather than a standalone diagnostic modality. When integrated with conventional MRI features and correlated with histopathology, choline detection and Cho/Cr ratios enhance lesion characterization and provide meaningful insights into tumor biology.

CONCLUSION

MRI spectroscopy significantly improves the evaluation of focal bone lesions by providing metabolic information that complements conventional MRI. Choline peak detection and elevated choline-to-creatine ratios are strongly associated with malignant pathology, aggressive MRI features, and higher histopathological grades. Incorporation of MRI spectroscopy into routine musculoskeletal MRI protocols may aid in differentiating benign from malignant bone lesions and in assessing tumor aggressiveness, thereby supporting more informed clinical decision-making.

Limitations

The study was conducted at a single tertiary care center, which may limit broader generalization of the results. The sample size, although adequate for analysis, may not capture the full spectrum of rare bone tumors. Technical limitations inherent to MRI spectroscopy, including susceptibility artifacts and voxel placement challenges, may have influenced spectral quality in some cases.

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