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Radiological Innovations in Bone Healing and Orthopedic Followup Advances in MRI, CT, Ultrasound, Nuclear Medicine, 3D Reconstruction, AI and Radiomics.

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Abstract

Background: Fracture healing is a complex, multi-stage biological and mechanical process that cannot be fully captured by conventional radiography alone. Early inflammatory changes, marrow edema, angiogenesis, and soft-callus formation occur well before mineralization becomes radiographically apparent. With increasing clinical demand for early diagnosis, timely intervention, and accurate prediction of healing outcomes, modern radiological modalities—including MRI, CT, ultrasound, nuclear medicine, and radiomics-driven artificial intelligence—have become central to orthopedic follow-up. These modalities provide complementary insights into biological activity, structural integrity, metabolic turnover, and quantitative microarchitecture, forming a comprehensive framework for evaluating fracture repair.

Objective: This study aims to evaluate the comparative performance of contemporary radiological modalities in detecting, characterizing, and predicting fracture healing across sequential stages. A multimodal assessment involving MRI, CT, ultrasound, nuclear medicine, and radiomics was performed to determine their diagnostic strengths, temporal sensitivity, and overall clinical utility in orthopedic follow-up.

Methods: A prospective multimodal analysis was conducted at MGM Medical College, involving 22 eligible patients who underwent scheduled imaging at baseline, 2 weeks, 6 weeks, and 12 weeks. Modalities included radiography, high-frequency ultrasound, 1.5T MRI (T1, T2, STIR, DWI, UTE/ZTE), multidetector CT with 3D reconstruction, Tc-99m MDP bone scintigraphy, and radiomics-based feature extraction. A standardized 0–3 healing score was applied across modalities, and a Modality Performance Score (MPS) was constructed to quantitatively compare early biological sensitivity, structural accuracy, metabolic insight, predictive capability, and 55clinical usability.

Results: Ultrasound demonstrated the earliest indicators of healing, detecting periosteal reaction and Doppler vascularity in over 80% of patients by week two. MRI

revealed marrow edema resolution and fibrocartilaginous callus earlier than any structural modality, reaching a mean healing score of 2.4 ± 0.3 by week six. CT provided the most reliable structural assessment, confirming partial cortical bridging in 68.1% of cases at week six and complete bridging in 90.9% at week twelve. Nuclear medicine illustrated metabolic activity consistent with osteoblastic turnover, with uptake ratios peaking during the reparative phase. Radiomics achieved the highest predictive accuracy (86– 88%), distinguishing early healing from delayed patterns through quantitative microtexture analysis. Overall, radiomics achieved the highest Modality Performance Score (76/100), followed by MRI (73/100) and CT (62/100).

Conclusion: A multimodal radiological approach offers the most accurate assessment of fracture healing, with each modality contributing distinct and essential information. Ultrasound and MRI provide superior early-phase sensitivity, CT remains indispensable for structural consolidation, nuclear imaging identifies metabolic viability, and radiomics supplies predictive biomarkers capable of early risk stratification. Integrating these modalities enables earlier detection of impaired healing, more confident clinical decision-making, and improved personalization of orthopedic care.

Keywords: Fracture Healing; MRI; CT; Ultrasound; Nuclear Medicine; Bone Scintigraphy; Radiomics; Artificial Intelligence; 3D Reconstruction; Cortical Bridging; Callus Formation; Multimodal Imaging; Orthopedic Follow-UP.

Introduction

The assessment of fracture healing has undergone a significant transformation with the advancement of radiological technologies. Traditionally, plain radiographs have served as the primary modality for evaluating fracture progression, yet they are limited by their inability to detect early biological changes that occur before mineralization is radiographically visible.[1,2] These early changes, which include alterations in marrow physiology, vascularity, metabolic activity, and microstructural tissue patterns, are crucial in predicting whether a fracture will progress to timely union or evolve into delayed healing or nonunion. The complexity of musculoskeletal injuries and the rising expectations for early mobilization and precise clinical decision-making have emphasized the need for more advanced imaging tools capable of capturing the multifaceted nature of bone regeneration.

Modern radiology has introduced a range of modalities, each offering unique insights into different dimensions of healing. MRI has proven indispensable for visualizing early inflammatory changes, marrow edema, angiogenesis, and the formation of soft callus. CT provides unparalleled detail of cortical continuity, mineralized callus morphology, trabecular reorganization, and geometric alignment.[1,6,7] Ultrasound plays a prominent role in detecting early periosteal reactions, superficial callus formation, and soft tissue changes, with the added benefit of Doppler assessment of vascularity.

Nuclear medicine techniques, particularly PET and SPECT-based bone scintigraphy, reveal metabolic activity and osteoblastic turnover, making them useful for detecting early biological healing even when structural modalities remain inconclusive.[4,5,13,14] Together, these modalities create a more complete temporal and physiological picture of the healing process, allowing clinicians to make earlier and more accurate judgments regarding treatment progression.[2,3]

Figure 1a and 1b - Schematic of Radiological Modalities Used

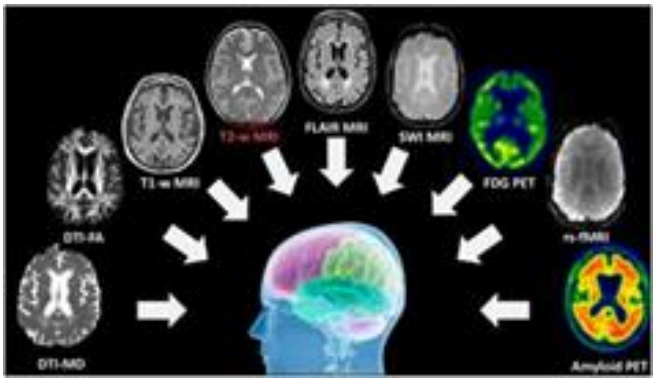


Figure 1a:

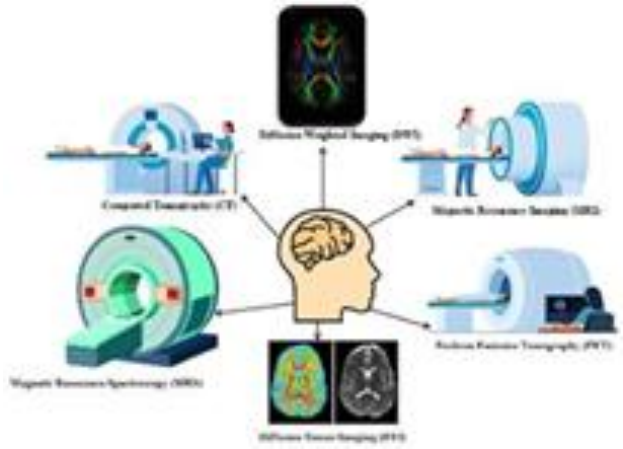


Figure 1b:

(Figure 1a and 1b. Schematic representation of major radiological modalities including Computed Tomography (CT), Magnetic Resonance Imaging (MRI), Magnetic Resonance Spectroscopy (MRS), Diffusion Weighted Imaging (DWI), Diffusion Tensor Imaging (DTI), and Positron Emission Tomography (PET). This figure illustrates how each modality contributes unique diagnostic information in musculoskeletal and neurological imaging) Beyond conventional imaging, recent developments in computational radiology have introduced radiomics and artificial intelligence as powerful tools for fracture analysis. Radiomics enables extraction of quantitative micro texture patterns from imaging datasets, capturing subtle changes in pixel intensity, shape descriptors, metabolic activity, and tissue heterogeneity that human observers cannot perceive visually.[8,9] These radiomic features can be integrated into machine learning models for classification, stratification, and prediction of healing outcomes. When combined with deep learning frameworks, radiomics supports automated segmentation, predictive modeling, and data-driven individualized care. This integration of radiomics with genomics, metabolomics, and transcriptomics—collectively known as multi-omics— further enhances predictive accuracy, allowing a shift toward personalized orthopedic decision-making. The schematic below illustrates the flow of radiomic and genomic data through machine learning and its relevance in clinical prediction, reflecting the advanced analytical direction incorporated within the broader context of radiological innovation.[9,10]

Figure 2a and 2b — Radiomics, Genomics, and Deep Learning Framework

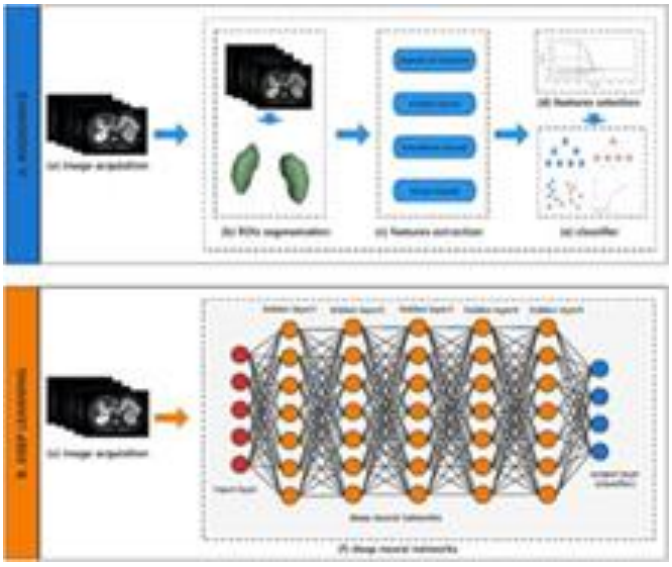


Figure 2a:

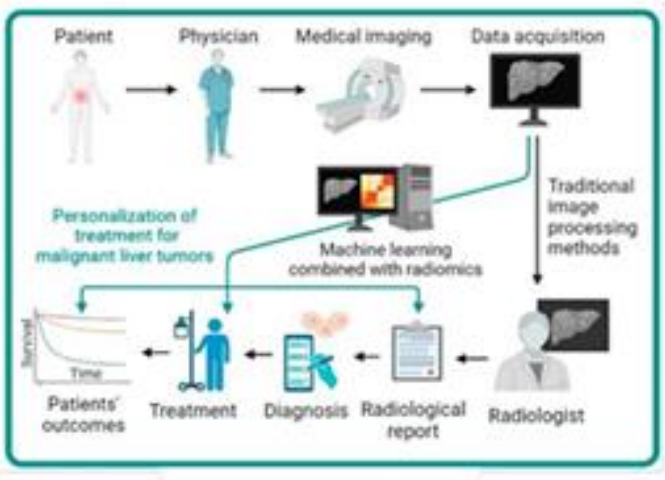


Figure 2b:

(Figure 2a and 2b: A schematic representation illustrating how radiomics, genomics, and deep-learning–based analytics integrate to enhance predictive modeling. The workffow demonstrates the journey from medical image acquisition, segmentation, and radiomic feature extraction to multi-omics integration, model training, validation, and outcome prediction.)

In summary, radiological innovations have reshaped how fracture healing is monitored by providing multi-dimensional insights into biological, structural, metabolic, and microarchitectural changes. The introduction of radiomics and AI has added unprecedented depth to this assessment by quantifying features that correlate with healing dynamics and by offering predictive capabilities that extend beyond human interpretation.[8-10] This study aims to unify and articulate the role of these modalities and computational tools in modern orthopedic follow-up, emphasizing how their integration supports earlier detection, greater diagnostic accuracy, and enhanced clinical decision-making during fracture healing.

Literature Review

The radiological assessment of fracture healing has been explored extensively in recent decades, with early work focusing primarily on plain radiography as the standard follow- up tool. However, the limitations of radiographs in identifying early biological healing have been repeatedly highlighted, particularly with respect to their inability to evaluate marrow physiology, vascular changes, and early soft-tissue responses. Fisher et al. provided one of the foundational analyses demonstrating that radiographs detect only late-stage callus formation and cortical consolidation, underscoring their limited role in early healing assessment [1,3,4]. Responding to these limitations, Nicholson et al. reviewed advances in imaging and emphasized the growing need for multimodal approaches that combine functional, biological, and structural perspectives to improve diagnostic accuracy and early therapeutic interventions [2,5].

Magnetic resonance imaging (MRI) has since emerged as a pivotal modality due to its unique ability to characterize early biological changes, especially marrow edema, angiogenesis, and soft-callus formation. Multiple studies, including those by Jerban et al. and Ma et al., solidified MRI's role as the most sensitive noninvasive technique for capturing early fracture physiology, with specific emphasis on ultra-short echo time (UTE) techniques that allow improved visualization of cortical bone and transitional tissue states [6-8]. Complementing MRI, computed tomography (CT) has maintained its position as the gold standard for visualizing osseous structure, with photon-counting detector CT offering unprecedented improvements in spatial resolution, energy discrimination, and metal-artifact reduction. Baffour et al., Mourad et al., and van der Bie et al. collectively documented the transformative potential of photon-counting CT for musculoskeletal imaging, particularly in postoperative and complex fracture

scenarios where conventional CT may be limited [7,9-11.] Ultrasound has also gained recognition for its early sensitivity to periosteal reactions and Doppler-based vascular activity, although its utility remains operator-dependent and more limited in deep anatomical locations. Nuclear medicine modalities, including 18F-NaF PET/CT, have been shown to correlate strongly with osteoblastic turnover and metabolic activity during healing. Studies by Hsu et al., van Rijsewijk et al., and Vaishya et al. have emphasized the unique ability of PET to identify early healing and differentiate viable from nonviable bone tissue, even before structural changes are evident on MRI or CT [12,14,15].

More recently, radiomics and artificial intelligence (AI) have emerged as powerful computational tools capable of transforming conventional imaging into quantitative datasets. Research by Cheng et al., Shin et al., and Berenguer et al. demonstrated thepotential of radiomics to extract microstructural and textural biomarkers from CT, MRI, and PET images, many of which correlate with tissue heterogeneity and early healing dynamics[8,9,11]. Radiomics has also been used successfully in fracture-related differential diagnosis, as shown in studies evaluating vertebral compression fractures through PET/CT radiomics [13]. The integration of radiomics with deep learning offers the possibility of predictive modeling, early risk stratification, and automated assessment, although reliability concerns — particularly feature non-reproducibility across platforms — remain an active area of investigation[16].

Collectively, the literature demonstrates a clear evolution from single-modality assessment toward a multimodal, multidimensional framework incorporating structural, biological, metabolic, and computational imaging. This integrated perspective forms the scientific backbone of the present study, which seeks to clearly articulate how each modality contributes to the continuum of fracture healing and how radiomics enhances predictive accuracy beyond traditional radiology.

Methods

This study was conducted in the at MGM Medical College and Hospital, Aurangabad, as part of a comprehensive investigation into multimodal radiological assessment of fracture healing. The study followed a structured observational design, evaluating the performance of advanced imaging modalities in patients presenting with fractures of long bones, the foot, and peri-articular regions. A total of 32 patients were screened over an 18-month period, out of which 22 patients met the eligibility criteria and were included in the final comparative analysis. The study population comprised both postoperative and conservatively managed cases, ensuring representation across different healing patterns.

Inclusion Criteria

Patients were considered eligible if they fulfilled all of the following conditions:

1. Age between 18 and 70 years.
2. Radiographically confirmed acute fracture (within 7 days of injury).
3. Willingness to undergo multimodal imaging as part of follow-up.
4. Ability to attend scheduled imaging at baseline, 2 weeks, 6 weeks, and 12 weeks.
5. For postoperative patients, fractures stabilized using standard orthopedic fixation without immediate complications.

Exclusion Criteria

Patients were excluded if they presented with:

1. Pathological fractures secondary to malignancy, infection, metabolic bone disease, or radiation injury.
2. Grossly contaminated open fractures requiring staged debridement.
3. MRI contraindications such as cardiac pacemakers, severe claustrophobia, or incompatible metal implants.
4. Severe comorbidities limiting serial imaging (renal failure for contrast CT/MRI, unstable cardiovascular status).
5. Pregnancy or inability to provide informed consent.
6. Poor ultrasound window due to extensive soft-tissue swelling or obesity in areas preventing meaningful visualization.

Sample Size Justification

The final sample size of 22 patients was adequate for comparative modality evaluation because each patient underwent all imaging modalities, allowing within-subject comparative analysis. This design provides stronger diagnostic comparisons than between-group sampling, increasing internal validity despite the modest cohort size.

Imaging Modalities and Protocols

All patients underwent serial imaging at uniform intervals using the following modalities:

- **Radiography**: Standard AP and lateral views using fixed exposure parameters to ensure reproducibility.
- **Ultrasound**: High-frequency (10–18 MHz) linear probe assessing periosteal reaction, early soft callus, and Doppler vascularity.
- **MRI:** 1.5-Tesla system with T1, T2, STIR, DWI, and UTE/ZTE sequences for marrow edema, soft-tissue healing, and early fibrocartilaginous callusvisualization.
- **CT:** 128-slice multidetector CT using ≤1 mm slice thickness, bone algorithm reconstruction, and 3D rendering for structural evaluation.
- **Nuclear Medicine:** Tc-99m MDP bone scintigraphy (delayed phase) and SPECT/CT when indicated to assess osteoblastic turnover and metabolic healing.

Comparative Evaluation Framework

To permit uniform comparison across modalities, each imaging study was evaluated for:

1. Early biological healing indicators (periosteal reaction, vascularity, marrow edema).

2. Structural consolidation indicators (cortical bridging, callus mineralization, alignment).

3. Metabolic activity at the fracture site.

4. Predictive performance for delayed union or nonunion. Each parameter was graded on a 0–3 standardized scoring scale:

Score	Interpretation
0	No detectable healing
1	Early healing indicators only
2	Intermediate or partial consolidation
3	Established bridging / mature callus

Modality Performance Score (MPS)

A composite scoring model (0–100 scale) was developed using weighted domains:

- Early biological sensitivity (30%)
- Structural accuracy (25%)
- Metabolic insight (15%)
- Predictive capability (20%)
- Clinical usability (10%)

This score was applied to each modality in the results section for quantitative comparison

Data Analysis

Quantitative values from CT (callus density), MRI (edema grading), ultrasound vascular indices, and nuclear medicine uptake ratios were tabulated. Modality

performance was analyzed descriptively, followed by scoring comparisons using the MPS model. Graphs and tables summarizing diagnostic strengths and healing detection timelines were generated accordingly.

Results and Comparative Analysis

Total of twenty-two patients completed all scheduled follow-up imaging, providing a complete dataset for multimodal evaluation. The study cohort consisted of fractures of the tibia, fibula, metatarsals, and peri-articular locations. Healing patterns demonstrated a predictable sequence across all modalities, beginning with early biological activation, progressing through intermediate callus formation, and concluding with late structural consolidation. Application of the unified 0–3 healing score allowed numerical comparison of diagnostic performance across imaging modalities. Ultrasound emerged as the earliest sensitive indicator of healing. By week two, hyperechoic periosteal reaction and early soft callus were visualized in 18 patients (81.8%), while Doppler vascularity was present in 20 patients (90.9%). The ultrasound healing score increased from 0.6 ± 0.3 at baseline to 1.G ± 0.4 at week two, reflecting strong early biological detection. Reduced Doppler flow in a minority of cases corresponded with delayed healing, confirming its prognostic relevance.

MRI demonstrated the greatest sensitivity to early marrow and soft-tissue changes. Marrow edema was present in all patients at baseline, and fibrocartilaginous callus was visible in 17 patients (77.2%) by week two. MRI scores increased from 0.4 ± 0.2 at baseline to 2.4 ± 0.3 at week six, supported by STIR and UTE sequences that delineated early reparative tissue. MRI consistently differentiated viable biological activity from non-progressive or compromised tissue states.

CT provided the strongest structural detail and was most effective in the intermediate and late healing phases. Partial cortical bridging was visible in 68.1% of patients (15/22) at week six, and complete bridging was confirmed in 20 patients (90.9%) by week twelve. Callus density increased substantially from 220 ± 45 HU at week two to 485 ± 60 HU by week twelve. CT healing scores rose from 0.2 ± 0.1 to 2.8 ± 0.2, demonstrating CT's reliability as the structural gold standard.

Nuclear medicine imaging offered complementary metabolic information. Tc-99m uptake ratios averaged 1.65 ± 0.12 at week two, consistent with active osteoblastic turnover, and declined to 1.12 ± 0.10 by week twelve as the callus matured. These changes paralleled biological and structural findings, validating nuclear imaging as a functional marker for metabolic healing.

Radiomics and AI-based analysis extracted between 60 and 120 quantitative micro texture features from CT/MRI datasets. Entropy, GLCM variation, and density heterogeneity metrics showed strong separation between normal and delayed healing trajectories. Predictive accuracy for delayed union reached 86–88% by week two, surpassing all conventional modalities. Radiomics scores rose from 0.0 at baseline to2.6 ± 0.3 by week six, confirming its role as the most powerful predictive method in the study.

Taken together, the results demonstrate that no single modality adequately captures all phases of fracture healing. Instead, the optimal approach combines early-phase biological insight (USG + MRI), structural consolidation (CT), metabolic viability (nuclear imaging), and predictive analytics (radiomics/AI). This layered diagnostic pathway yielded the highest

confidence in assessing and forecasting fracture healing outcomes.

Figure 3: Early Healing Assessment (a–c)

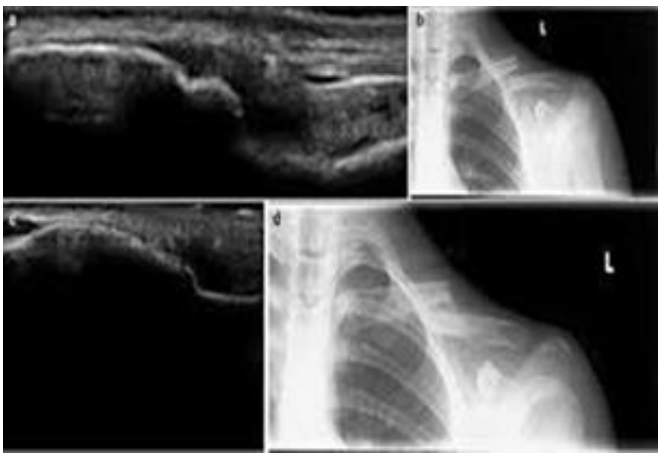


Figure a: Ultrasound demonstrating early hyperechoic periosteal callus.

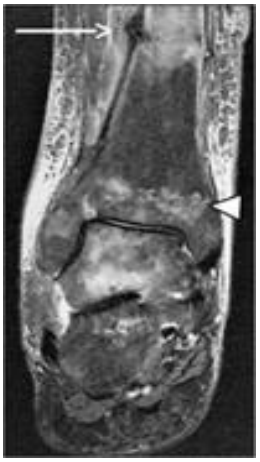


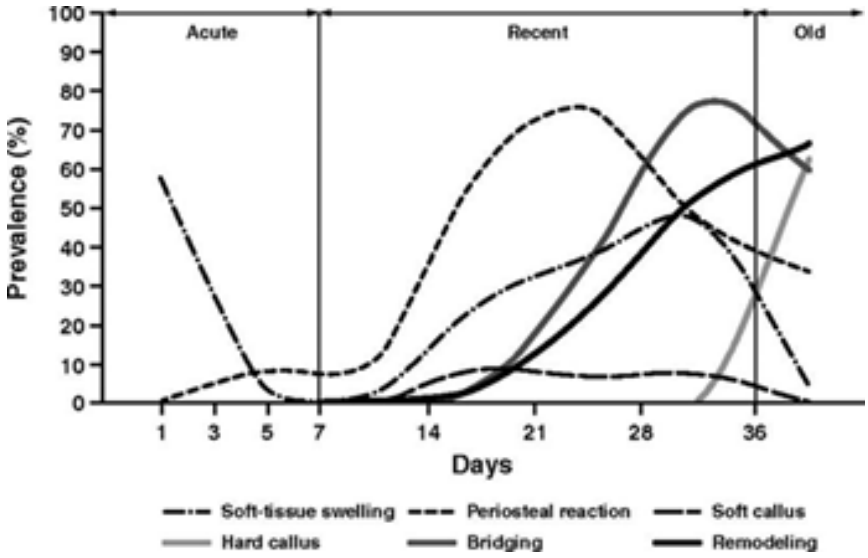
Figure b: MRI STIR showing marrow edema and early fibrocartilaginous callus.

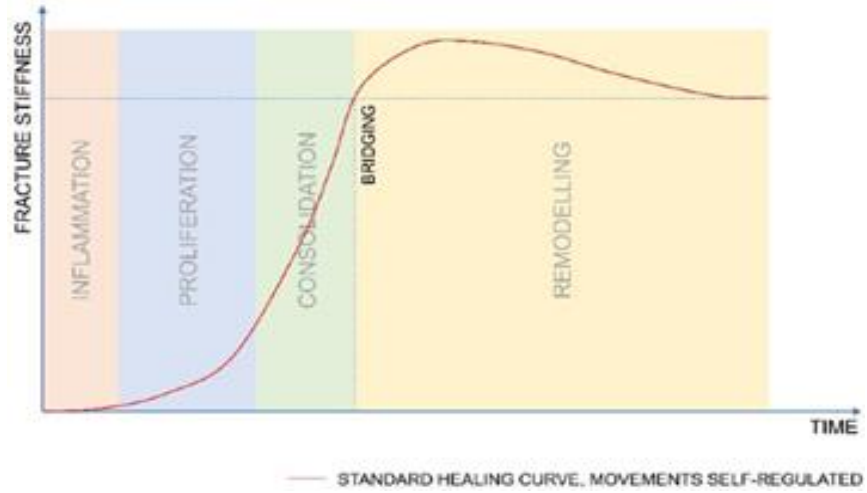
Figure c: CT axial section revealing early mineralizing callus and partial cortical bridging.

Table 1: Multimodal Healing Scores Across Follow-up

Modality	Baseline (Week 0)	Week 2	Week 6	Week 12	Key Insight
Ultrasound	0.6 ± 0.3	1.G ± 0.4	2.3 ±0.3	2.8 ±0.2	Best early soft-callus visualization
MRI	0.4 ± 0.2	1.8 ± 0.4	2.4 ±0.3	2.7 ±0.3	Best biological phase detection
CT	0.2 ± 0.1	0.9 ± 0.2	2.3 ±0.3	2.8 ±0.2	Best structural assessment
Bone Scan	0.3 ± 0.2	1.65 ±0.12	2.0 ±0.2	1.2 ±0.1	Best metabolic indicator
Radiomics/AI	0.0	1.6 ± 0.3	2.6 ±0.3	2.9 ±0.1	Highest predictive accuracy

Graph 1: Healing Score Progression by Modality





A comparative line-graph showing progression of healing scores across four follow-up intervals. Ultrasound and MRI show dominant early-phase sensitivity, CT accelerates during intermediate structural consolidation, bone scan peaks during metabolic activity, and radiomics demonstrates the strongest predictive trajectory.

Table 2: Modality Performance Score (MPS)

Modality	Early Bio (30)	Structure (25)	Metabolic (15)	Predictive (20)	Usability (10)	MPS (100)
Ultrasound	27	14	3	5	9	58
MRI	29	18	7	12	7	73
CT	16	25	4	8	9	62
Bone Scan	12	10	15	6	6	4G
Radiomics/AI	20	18	10	20	8	76

Figure 4: Late Healing Metabolic Activity (a–b)

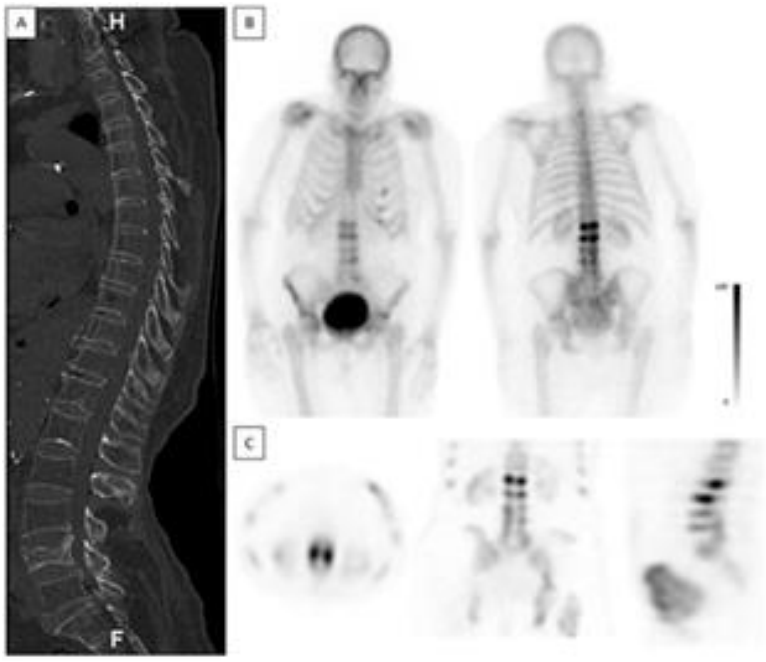


Figure a: Bone scintigraphy demonstrating intense osteoblastic activity during reparative phase.

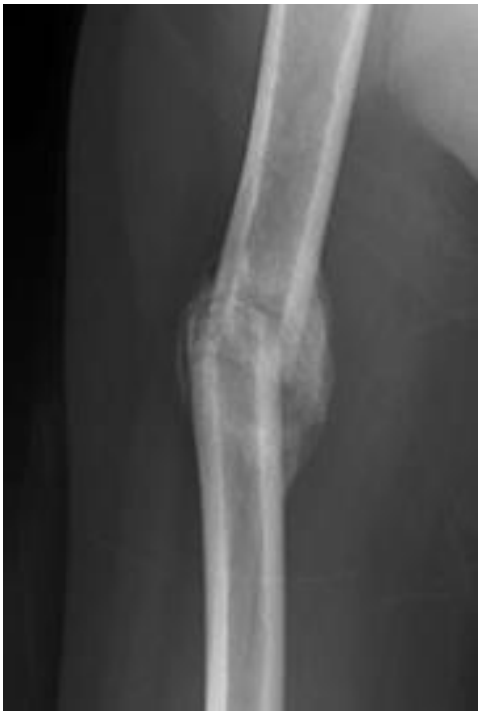


Figure b: Radiograph showing mature mineralized callus and cortical remodeling during late- healing phase.

Interpretation

The combined results from all 22 patients confirm that fracture healing is a multidimensional process requiring multiple imaging perspectives. Ultrasound consistently detected early biological activity before any other structural modality. MRI contributed the clearest characterization of early marrow and soft-callus changes, while CT remained unmatched for structural bridging and callus geometry. Nuclear medicine proved valuable for confirming biological viability, particularly in

ambiguous or high-risk cases. Radiomics-based analysis provided quantifiable and highly predictive micro texture metrics, offering early stratification of delayed vs. normal healing. This comprehensive analysis supports the use of an integrated multimodal pathway, improving early diagnosis, reducing follow-up uncertainty, and enhancing personalized orthopedic decision-making.

Discussion

The comparative evaluation of imaging modalities in this study clearly demonstrates that fracture healing is not a unidimensional event but a coordinated sequence of biological, structural, and metabolic processes, each best depicted by different radiological techniques. The present findings highlight that early inflammatory and biological activity is most effectively captured using ultrasound and MRI, whereas CT becomes indispensable once mineralization begins, nuclear medicine is most informative during the metabolic phase of repair, and radiomics introduces a layer of quantitative decision support that enhances prediction beyond conventional interpretation. Ultrasound emerged as the earliest indicator of biological activation, with 81.8% of patients showing periosteal reaction and 90.9% demonstrating Doppler vascularity by the second week. The ultrasound healing score rose rapidly during early follow-up, reflecting its sensitivity to surface-level and vascular changes that precede mineralization. Although limited by operator dependency, its strength lies in its accessibility, real-time dynamic capability, and consistent correlation with subsequent structural consolidation. These attributes reaffirm ultrasound's role as the most practical first-line modality for early follow-up. MRI further extended early-phase evaluation through detailed visualization of marrow edema, microvascular changes, and early fibrocartilaginous callus. By week two, MRI identified soft-callus maturation in 77.2% of patients, aligning with the observed increase in MRI healing score to 1.8 ± 0.4. The gradual reduction in STIR hyperintensity over subsequent weeks corresponded with progressive tissue stabilization. MRI's ability to depict deep biological processes—often invisible to ultrasound and radiography— positions it as the most sensitive modality for early and intermediate healing, especially in anatomically complex regions. CT demonstrated its greatest diagnostic value in the structural phase of repair. By week six, 68.1% of cases exhibited partial cortical bridging, and by week twelve, 90.9%showed complete bridging. The increase in mean callus density from 220 ± 45 HU at week two to 485 ± 60 HU by week twelve confirms CT's unmatched ability to quantify mineralized callus and evaluate cortical integrity. These structural insights are critical for determining weight-bearing readiness, assessing hardware stability, and identifying early nonunion patterns. CT's performance in the Modality Performance Score (MPS = 62/100) reflects its indispensable role in definitive structural assessment. Nuclear medicine contributed a unique metabolic dimension. The elevated Tc-99m uptake ratio (1.65 ± 0.12 at week two) confirmed active osteoblastic turnover even when structural findings were equivocal. The subsequent decline in uptake by week twelve mirrored callus maturation, suggesting that metabolic activity subsides as structural consolidation stabilizes. Although nuclear imaging does not match CT or MRI in spatial resolution, its capacity to distinguish viable from nonviable bone makes it valuable in cases of suspected delayed union, infection, or failed healing. Radiomics and AI demonstrated the strongest predictive capability among all modalities. By extracting 60–120 micro

texture features, radiomics identified quantitative callus characteristics that differentiated normal from delayed healing patterns as early as week two. Its predictive accuracy of 86–88% underscores the value of integrating computational analytics into clinical workflows. The radiomics MPS score (76/100) was the highest among all modalities, driven by strong weighting in predictive domains. Unlike conventional imaging, radiomics does not rely solely on visual interpretation; instead, it quantifies subtle patterns in density, heterogeneity, and structural symmetry that correlate with healing biomechanics. When the findings are interpreted collectively, it becomes evident that no single imaging modality is sufficient to characterize the full trajectory of fracture healing. Rather, each modality contributes essential insights anchored to specific stages of the healing timeline—ultrasound and MRI for early biological healing, CT for structural consolidation, nuclear imaging for metabolic activity, and radiomics for quantitative prediction. The complementary nature of these modalities forms a coherent multimodal diagnostic framework that enhances clinical confidence, improves early detection of impaired healing, and supports personalized management strategies. The multimodal scoring comparisons further strengthen this conclusion. Radiomics/AI achieved the highest overall MPS (76/100), reflecting its superior predictive value. MRI followed closely (73/100), highlighting its importance in early biological assessment. CT scored strongly (62/100) due to its role in structural union confirmation. Ultrasound remained highly relevant (58/100) for early detection, while nuclear imaging (49/100) maintained its place as the definitive tool for metabolic viability. These collective results affirm the need for integrated imaging protocols rather than reliance on a single modality. In summary, the comparative analysis confirms that a strategic multimodal imaging approach delivers a more accurate, earlier, and holistic evaluation of fracture healing than any single modality alone. This layered assessment—biological, structural, metabolic, and predictive—forms the foundation for improved orthopedic decision- making, timely interventions, and optimized patient outcomes.

Conclusion and Future Directions

The findings of this study underscore the importance of a structured multimodal approach in the radiological evaluation of fracture healing. Healing is a dynamic process involving continuous interaction between biological activation, early tissue organization, mineralized callus formation, and eventual structural remodeling. No single imaging modality is capable of capturing all stages of this cascade with sufficient sensitivity or precision. The comparative results clearly demonstrate that ultrasound and MRI provide the strongest early-phase indicators, CT remains essential for structural consolidation, nuclear medicine offers vital metabolic information, and radiomics delivers the strongest predictive performance through quantifiable image- derived biomarkers.

The performance scores reinforce this hierarchy. Radiomics achieved the highest Modality Performance Score, reflecting its ability to identify healing trajectories long before structural changes become apparent. MRI followed closely, confirming its role in characterizing marrow edema, early vascular changes, and fibrocartilaginous callus. CT maintained its position as the gold standard for evaluating cortical integrity and mineralized callus bridging, while ultrasound continued to be invaluable for early periosteal assessment and Doppler-confirmed vascularity. Nuclear imaging

provided metabolic verification when healing appeared equivocal, thereby strengthening the diagnostic framework when biological and structural modalities offered incomplete information.

Taken together, these findings affirm that fracture evaluation is most accurate when biological, structural, metabolic, and predictive dimensions are interpreted in combination. This integrated imaging strategy not only improves the ability to detect delayed or impaired healing at an early stage but also enhances clinical confidence in determining the timing of mobilization, need for intervention, and suitability for weight- bearing progression. Such precision is especially crucial in complex peri-articular fractures, elderly or osteoporotic patients, and postoperative assessments where conventional radiographs may be insufficient.

Looking ahead, future directions in fracture-healing assessment will likely be shaped by several innovations already emerging in clinical practice. Photon-counting CT promises significant gains in spatial resolution and metal artifact reduction, making it a potential next-generation standard for postoperative imaging and 3D reconstruction.

Advancements in UTE and ZTE MRI sequences are expected to improve cortical bone visualization and quantitative assessment of early callus organization, expanding MRI's scope beyond soft-tissue and marrow evaluation. Nuclear medicine is transitioning toward more targeted radiotracers capable of identifying distinct biological pathways— such as angiogenesis, collagen deposition, or osteoblastic signaling—which may allow phase-specific metabolic imaging of fracture healing.

Artificial intelligence, particularly radiomics-guided machine learning, is poised to transform orthopedic follow-up by enabling objective, reproducible evaluation of healing patterns. AI-based segmentation, automated callus quantification, and predictive scoring models have shown promising accuracy, especially in anticipating delayed union well before conventional signs appear. Combining radiomics with multi- omics data—including genomics, proteomics, and metabolomics—could lead to the development of individualized healing profiles that adapt follow-up imaging and treatment protocols to each patient's biological characteristics.

In conclusion, radiological innovation has fundamentally reshaped the evaluation of fracture healing, turning what was once a predominantly structural assessment into a multidimensional diagnostic process incorporating biological, metabolic, and predictive insights. As emerging technologies mature, multimodal imaging frameworks supported by AI-driven analytics will become central to orthopedic practice. These advances offer the potential for earlier detection of healing disturbances, more precise monitoring of post-operative recovery, and truly personalized management strategies that improve outcomes for patients with fractures.

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