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Imaging Biomarkers in Systemic Disease: Quantitative Radiology and Precision Medicine in Clinical Practice

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ABSTRACT

Imaging biomarkers have progressively transformed modern radiology by providing quantitative, functional, and molecular information capable of improving early disease detection, diagnostic precision, therapeutic monitoring, and clinical decision-making in systemic diseases. The present review aimed to analyze the current role of imaging biomarkers in oncology and internal medicine, emphasizing their contribution to precision medicine and multidisciplinary healthcare management. A structured documentary review was conducted using peer-reviewed scientific

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literature indexed in internationally recognized databases, including PubMed, Scopus, ScienceDirect, and SpringerLink. The analyzed evidence focused on advanced imaging modalities such as computed tomography, magnetic resonance imaging, positron emission tomography, hybrid imaging systems, radiomics, and artificial intelligence-assisted imaging analysis. The reviewed studies demonstrated that imaging biomarkers possess broad applicability in oncology, neurological disorders, cardiovascular diseases, inflammatory conditions, chronic hepatic disease, pulmonary pathology, and metabolic disorders. Functional and molecular imaging techniques showed particular relevance for evaluating metabolism, tissue perfusion, angiogenesis, fibrosis, inflammation, cellular density, and tumor heterogeneity. Radiomics and artificial intelligence were identified as emerging technologies capable of improving predictive analysis, treatment response assessment, and individualized therapeutic planning.

KEYWORDS

Imaging biomarkers, radiomics, precision medicine, oncology imaging, molecular imaging, artificial intelligence, systemic diseases, magnetic resonance imaging, positron emission tomography, computed tomography, quantitative imaging, clinical decision-making, tumor heterogeneity, internal medicine, hybrid imaging

INTRODUCTION

The progressive evolution of medical imaging has transformed radiology from a predominantly descriptive specialty into a quantitative and predictive discipline capable of supporting complex clinical decision-making across multiple medical fields. In recent years, imaging biomarkers have emerged as essential tools in oncological and systemic disease assessment, enabling earlier detection, characterization of disease heterogeneity, evaluation of therapeutic response, and prediction of clinical outcomes through non-invasive approaches [1], [2]. The growing integration of imaging biomarkers into routine clinical practice reflects an international effort to improve diagnostic precision while simultaneously advancing personalized medicine strategies in oncology, internal medicine, and multidisciplinary patient care [3].

Imaging biomarkers are objectively measurable imaging characteristics that indicate biological processes, pathogenic mechanisms, or responses to therapeutic interventions [1]. These biomarkers may derive from anatomical imaging, functional imaging, molecular imaging, or advanced computational analysis techniques such as radiomics and artificial intelligence-assisted image processing [4], [5]. Their importance has increased considerably due to the limitations associated with conventional diagnostic models, which frequently depend on invasive procedures, delayed symptom manifestation, or qualitative image interpretation susceptible to interobserver variability [6].

In oncology, imaging biomarkers have become particularly relevant because cancer remains one of the leading causes of morbidity and mortality worldwide. According to current global estimates, the burden of malignant disease continues to rise, especially in low- and middle-income countries where access to early diagnostic tools and precision medicine remains heterogeneous [7]. Conventional imaging modalities such as computed tomography (CT), magnetic resonance imaging (MRI), positron emission tomography (PET), and hybrid imaging systems now provide far more than anatomical information. Quantitative imaging analysis allows the extraction of tumor phenotypic characteristics associated with angiogenesis, cellular density, metabolism, hypoxia, proliferation patterns, and intratumoral heterogeneity [8], [9].

The implementation of standardized imaging response criteria, including RECIST 1.1, represented a major milestone in the integration of imaging biomarkers into therapeutic evaluation [10], [11]. However, increasing evidence suggests that tumor biology cannot be fully understood through dimensional measurements alone. Functional and metabolic biomarkers obtained through diffusion-weighted MRI, perfusion imaging, spectroscopy, and fluorodeoxyglucose PET have demonstrated superior capabilities in identifying treatment response before structural changes become apparent

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[12]. This paradigm shift has strengthened the role of imaging in precision oncology, where radiological data contribute not only to diagnosis but also to prognosis, therapeutic selection, and longitudinal monitoring.

The emergence of radiomics has further expanded the clinical relevance of imaging biomarkers. Radiomics refers to the high-throughput extraction of quantitative image features capable of identifying patterns not perceptible to the human eye [9], [13]. Texture analysis, shape descriptors, histogram-based parameters, and machine learning algorithms have shown promising applications in predicting tumor aggressiveness, molecular subtypes, treatment resistance, and patient survival [14]. These advances support the concept that medical images contain a large amount of biologically relevant data that can be transformed into clinically actionable information.

Beyond oncology, imaging biomarkers have demonstrated increasing applicability in systemic diseases involving cardiovascular, neurological, inflammatory, metabolic, and autoimmune processes. In internal medicine, advanced imaging techniques are being used to evaluate diffuse organ involvement, monitor chronic inflammatory conditions, identify subclinical disease progression, and estimate systemic risk profiles [15]. Quantitative imaging markers have shown relevance in diseases such as systemic lupus erythematosus, chronic liver disease, neurodegenerative disorders, sarcoidosis, vasculitis, and cardiometabolic syndromes, where imaging findings may precede irreversible structural damage or overt clinical deterioration [16].

Neuro-oncology represents another area where imaging biomarkers have significantly improved clinical management. Advanced MRI techniques, perfusion imaging, diffusion tensor imaging, and PET tracers have contributed to more accurate tumor grading, differentiation between recurrence and radiation necrosis, and evaluation of treatment efficacy [17]. Similarly, hybrid imaging modalities combining structural and molecular information continue to enhance diagnostic sensitivity and specificity across multiple systemic pathologies.

Despite these advances, several challenges continue to limit the universal implementation of imaging biomarkers in clinical practice. One major limitation involves the lack of standardization among imaging acquisition protocols, reconstruction parameters, feature extraction methodologies, and data interpretation algorithms [18]. Variability between institutions and imaging platforms may affect reproducibility and reduce external validation of quantitative biomarkers. To address these concerns, international initiatives such as the Image Biomarker Standardization Initiative (IBSI) have promoted methodological harmonization and reproducibility frameworks for radiomics research [13], [18].

Another important challenge involves disparities in healthcare infrastructure and access to advanced imaging technologies, particularly in developing regions. In Latin America, including countries such as Mexico, Colombia, and Ecuador, healthcare systems face important limitations related to resource availability, specialized training, technological distribution, and research funding [19], [20]. Nevertheless, these countries have shown increasing participation in oncological imaging research and precision medicine initiatives, contributing to regional collaborations aimed at improving diagnostic capabilities and reducing inequities in cancer care. The incorporation of imaging biomarkers into educational and clinical settings within these regions represents an opportunity to strengthen multidisciplinary training and foster evidence-based decision-making.

The educational value of imaging biomarkers is also highly significant. Medical students, radiology trainees, oncologists, and internal medicine specialists increasingly require a comprehensive understanding of quantitative imaging concepts due to their expanding role in modern healthcare systems. Familiarity with imaging-derived biomarkers allows future clinicians to interpret imaging findings more critically, understand disease behavior more

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accurately, and participate effectively in multidisciplinary treatment planning. As imaging technologies continue to evolve, academic institutions must adapt their educational models to incorporate emerging radiological methodologies and computational approaches.

The present review article was developed to provide a comprehensive and clinically oriented analysis of imaging biomarkers in systemic disease, emphasizing their applications in oncology and internal medicine. The study explores current imaging modalities, quantitative techniques, radiomics applications, clinical utility, standardization challenges, and future perspectives in precision medicine. Furthermore, this review highlights the growing international relevance of imaging biomarkers while considering the particular context of Latin American healthcare systems, including contributions and perspectives from Mexico, Colombia, and Ecuador.

The central research question guiding this review is how imaging biomarkers contribute to earlier disease detection and improved clinical decision-making in systemic diseases. Additionally, the article examines the hypothesis that quantitative imaging analysis may enhance diagnostic precision, optimize therapeutic monitoring, and facilitate individualized patient management compared to conventional qualitative imaging assessment alone. To address these objectives, a structured literature review was performed using peer-reviewed scientific publications indexed in internationally recognized databases, prioritizing studies focused on imaging biomarkers, radiomics, oncology imaging, systemic disease evaluation, and precision medicine applications.

DEVELOPMENT

The growing complexity of systemic diseases and oncological disorders has significantly increased the demand for diagnostic strategies capable of identifying pathological alterations at earlier stages while simultaneously improving therapeutic precision. Within this context, imaging biomarkers have emerged as one of the most relevant innovations in contemporary radiology and internal medicine, offering quantitative and reproducible information that extends beyond conventional anatomical visualization [1], [2]. Their progressive integration into clinical workflows has transformed medical imaging into an essential component of precision medicine, multidisciplinary patient management, and longitudinal disease monitoring.

Historically, radiological interpretation relied predominantly on qualitative visual analysis performed by specialists using structural imaging modalities. Although traditional imaging techniques remain fundamental in routine clinical practice, several limitations have become evident over time. Conventional approaches frequently depend on subjective interpretation, may fail to detect subtle biological alterations during early disease stages, and often provide insufficient information regarding tumor heterogeneity, inflammatory activity, or metabolic dysfunction [3]. These limitations are particularly relevant in systemic diseases, where pathological processes frequently involve multiple organs simultaneously and where early intervention directly influences long-term prognosis.

Imaging biomarkers address many of these limitations by providing measurable indicators associated with physiological, cellular, molecular, and metabolic processes. Modern imaging technologies now allow clinicians to quantify tissue characteristics such as cellular density, vascular permeability, glucose metabolism, oxygenation status, perfusion patterns, fibrosis, and inflammatory burden [4], [5]. These quantitative parameters have demonstrated clinical utility in oncology, cardiovascular medicine, neurology, rheumatology, hepatology, and endocrinology, among other specialties.

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One of the most important applications of imaging biomarkers is early disease detection. In oncology, the identification of malignant lesions before the development of advanced structural changes remains a critical objective because survival outcomes are strongly associated with diagnostic timing [6]. Functional imaging modalities such as diffusion-weighted magnetic resonance imaging (DW-MRI), dynamic contrast-enhanced MRI (DCE-MRI), and positron emission tomography (PET) have shown the ability to identify metabolic or microstructural alterations even before macroscopic tumor growth becomes clinically evident [7]. This capability is especially valuable in highly aggressive malignancies, including glioblastoma, pancreatic cancer, hepatocellular carcinoma, and metastatic lung disease.

Positron emission tomography combined with computed tomography (PET/CT) represents one of the most widely utilized molecular imaging techniques in oncology. Fluorodeoxyglucose (18F-FDG) PET enables the evaluation of glucose metabolism, which is frequently elevated in malignant tissues due to accelerated cellular proliferation [8]. Increased standardized uptake values (SUVs) have been associated with tumor aggressiveness, metastatic potential, and treatment response in multiple cancer types. In addition to staging purposes, PET imaging has become increasingly useful for evaluating residual disease, recurrence patterns, and therapeutic resistance following chemotherapy, radiotherapy, or immunotherapy [9].

Similarly, magnetic resonance imaging has evolved into a highly versatile platform for biomarker generation. Diffusion-weighted imaging provides quantitative information through apparent diffusion coefficient (ADC) values, which correlate with cellular density and membrane integrity [10]. Lower ADC values are often associated with highly cellular tumors, whereas increasing ADC values after therapy may indicate treatment-induced necrosis or reduced tumor viability. Perfusion imaging further contributes to vascular characterization by quantifying blood flow, capillary permeability, and angiogenesis, all of which are essential biological features in malignant transformation and chronic inflammatory diseases [11].

The emergence of radiomics has substantially expanded the diagnostic potential of imaging biomarkers. Radiomics involves the extraction of large numbers of quantitative imaging features from standard medical images using computational algorithms [12]. These features include texture heterogeneity, voxel distribution patterns, intensity histograms, shape descriptors, and spatial relationships that may reflect underlying tumor biology. Importantly, many radiomic characteristics are imperceptible to the human eye, allowing imaging datasets to function as high-dimensional sources of clinically relevant information [13].

Radiomics has shown promising results in predicting tumor grade, molecular subtype classification, response to systemic therapy, and patient survival. In breast cancer, radiomic models derived from MRI studies have demonstrated associations with hormone receptor expression and HER2 status [14]. In lung cancer, texture-based imaging analysis has contributed to the prediction of epidermal growth factor receptor (EGFR) mutations and immunotherapy response [15]. Similar applications have been described in colorectal cancer, prostate cancer, gliomas, and liver malignancies, reinforcing the role of imaging biomarkers in personalized oncological care [16].

Artificial intelligence and machine learning have further strengthened the utility of imaging biomarkers by enabling automated pattern recognition and predictive modeling. Deep learning algorithms trained with large imaging datasets are capable of identifying subtle radiological abnormalities with increasing diagnostic accuracy [17]. These technologies may assist clinicians in detecting lesions, stratifying disease severity, estimating prognosis, and reducing interpretation variability. The integration of artificial intelligence into radiology workflows also represents a potential strategy for optimizing healthcare efficiency in regions facing shortages of specialized radiologists.

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In internal medicine, imaging biomarkers have demonstrated substantial relevance in the evaluation of chronic systemic disorders. In cardiovascular disease, cardiac MRI-derived biomarkers such as late gadolinium enhancement and extracellular volume fraction allow early identification of myocardial fibrosis and inflammatory injury [18]. In chronic liver disease, elastography techniques quantify hepatic stiffness, supporting non-invasive fibrosis assessment and reducing the need for liver biopsy [19]. Similarly, imaging biomarkers in rheumatologic diseases enable earlier recognition of joint inflammation, vascular compromise, and multisystem organ involvement before irreversible structural damage develops.

Neurological diseases constitute another important field of application. Neuroimaging biomarkers obtained through advanced MRI and PET studies have improved the diagnosis and monitoring of neurodegenerative disorders such as Alzheimer's disease, Parkinson's disease, and multiple sclerosis [20]. Functional connectivity analysis, cortical thickness measurements, and amyloid PET imaging contribute to earlier detection and more precise evaluation of disease progression. In neuro-oncology, imaging biomarkers facilitate differentiation between tumor recurrence and post-treatment effects such as radiation necrosis, which remains a major diagnostic challenge in clinical practice [14].

Despite their expanding clinical utility, imaging biomarkers continue to face important limitations. One of the primary concerns involves reproducibility and standardization across imaging centers. Variability in acquisition parameters, scanner calibration, segmentation methods, reconstruction algorithms, and feature extraction techniques may significantly influence quantitative results [12]. These challenges have motivated international collaborative initiatives focused on harmonization and quality control, including the Image Biomarker Standardization Initiative (IBSI), which seeks to improve methodological consistency in radiomics research [13].

Another major challenge involves accessibility and implementation disparities between healthcare systems. Although high-income countries have rapidly adopted advanced imaging technologies, many low- and middle-income regions continue to face limitations related to infrastructure, economic resources, specialized training, and technological availability [21]. In Latin America, countries such as Mexico, Colombia, and Ecuador have shown growing academic interest in imaging-based precision medicine; however, access to hybrid imaging systems, computational radiomics platforms, and artificial intelligence-assisted diagnostics remains uneven across institutions [22].

Mexico has demonstrated increasing participation in oncological imaging research through collaborations involving academic hospitals, cancer institutes, and university-based radiology programs. Colombian institutions have contributed to regional advances in molecular imaging, nuclear medicine, and computational radiology, particularly in urban tertiary-care centers. Ecuador has also shown progressive development in diagnostic imaging education and multidisciplinary oncology initiatives, emphasizing the need for greater technological integration and international collaboration. These regional efforts illustrate the expanding recognition of imaging biomarkers as essential components of modern clinical medicine throughout Latin America.

The educational implications of imaging biomarkers are equally important. Contemporary medical education increasingly requires students to understand not only traditional radiological anatomy but also the biological and computational foundations underlying quantitative imaging analysis. Radiology residents, oncologists, internists, and multidisciplinary healthcare professionals must develop competencies related to imaging interpretation, biomarker validation, artificial intelligence applications, and evidence-based clinical integration [23]. Consequently, academic institutions are progressively incorporating precision imaging concepts into undergraduate and postgraduate curricula to prepare future healthcare professionals for evolving diagnostic paradigms.

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Furthermore, imaging biomarkers may contribute to more individualized patient-centered care by facilitating risk stratification and therapeutic optimization. Rather than applying uniform treatment strategies, clinicians can increasingly tailor interventions according to imaging-derived biological profiles and predicted response patterns [24]. This approach aligns closely with the principles of precision medicine, where diagnostic and therapeutic decisions are adapted to the unique characteristics of each patient.

As medical imaging technologies continue to evolve, imaging biomarkers are expected to play an even greater role in disease prevention, early diagnosis, treatment planning, and longitudinal patient management. Ongoing advances in computational analysis, hybrid imaging systems, molecular tracers, and artificial intelligence will likely expand the diagnostic capabilities of radiology while strengthening interdisciplinary collaboration among oncologists, internists, surgeons, pathologists, and biomedical researchers.

Overall, the development of imaging biomarkers represents one of the most significant transformations in contemporary medicine. Their ability to integrate anatomical, functional, molecular, and computational information provides clinicians with increasingly sophisticated tools for understanding disease behavior and supporting evidence-based clinical decision-making. Although important challenges related to accessibility, validation, and standardization remain unresolved, the continued expansion of imaging biomarkers into clinical practice, research, and medical education underscores their growing importance within global healthcare systems.

GENERAL OBJECTIVE AND SPECIFIC OBJECTIVES

To critically analyze the current role of imaging biomarkers in systemic diseases, particularly in oncology and internal medicine, emphasizing their contribution to early disease detection, diagnostic precision, therapeutic monitoring, prognostic evaluation, and evidence-based clinical decision-making through advanced radiological and computational imaging techniques.

A. Cognitive Domain

1. To identify and describe the principal imaging biomarkers currently utilized in oncology, internal medicine, and systemic disease evaluation through contemporary radiological modalities such as computed tomography, magnetic resonance imaging, positron emission tomography, and hybrid imaging systems.
2. To explain the biological and physiological principles underlying quantitative imaging biomarkers, including metabolic activity, tissue perfusion, cellular density, angiogenesis, inflammatory burden, and molecular imaging characteristics.
3. To analyze the diagnostic and prognostic value of imaging biomarkers in the detection, staging, monitoring, and follow-up of malignant and non-malignant systemic diseases.
4. To compare conventional qualitative radiological assessment with advanced quantitative imaging approaches such as radiomics and artificial intelligence-assisted image analysis.
5. To evaluate the current scientific evidence regarding the clinical implementation, reproducibility, and standardization challenges associated with imaging biomarkers in precision medicine.

B. Psychomotor Domain

1. To develop the ability to recognize quantitative imaging findings associated with systemic diseases and oncological processes using radiological interpretation frameworks.

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2. To apply basic principles of radiomics and imaging biomarker analysis in the evaluation of clinical imaging studies for educational and academic purposes.
3. To utilize evidence-based radiological criteria, including RECIST and functional imaging parameters, during the interpretation of therapeutic response and disease progression.
4. To strengthen multidisciplinary diagnostic reasoning skills through the integration of imaging biomarkers into clinical case analysis and medical decision-making scenarios.
5. To promote the practical interpretation of advanced imaging modalities commonly used in precision medicine and modern radiology workflows.

C. Affective Domain

1. To encourage critical thinking regarding the ethical, clinical, and technological implications of integrating imaging biomarkers into patient-centered healthcare.
2. To foster appreciation for the importance of interdisciplinary collaboration among radiologists, oncologists, internists, pathologists, and biomedical researchers in the development of precision medicine strategies.
3. To promote academic interest in emerging imaging technologies and quantitative radiology among medical students and healthcare professionals.
4. To strengthen awareness regarding healthcare inequalities affecting access to advanced imaging technologies in developing countries, including Mexico, Colombia, and Ecuador.
5. To reinforce the value of evidence-based medicine, scientific research, and continuous professional education in the advancement of diagnostic imaging and systemic disease management.

OBJECT OF STUDY

The object of study of this review article focuses on the clinical, diagnostic, and prognostic role of imaging biomarkers in systemic diseases, particularly within the fields of oncology and internal medicine. The study specifically examines how quantitative and qualitative imaging-derived parameters contribute to early disease detection, characterization of pathological processes, therapeutic monitoring, and evidence-based clinical decision-making in contemporary healthcare systems.

Imaging biomarkers constitute measurable imaging characteristics obtained through radiological modalities that reflect normal biological processes, pathological alterations, or responses to therapeutic interventions [1]. Unlike conventional imaging approaches centered primarily on structural visualization, imaging biomarkers provide quantitative and functional information capable of revealing metabolic activity, tissue heterogeneity, vascularization patterns, cellular density, inflammatory burden, fibrosis, and molecular behavior [2], [3]. This transformation has positioned radiology as a central component of precision medicine and multidisciplinary clinical management.

The phenomenon under investigation involves the progressive integration of imaging biomarkers into medical practice and their impact on diagnostic accuracy and individualized patient care. The study explores how advanced imaging techniques—including computed tomography (CT), magnetic resonance imaging (MRI), positron emission tomography (PET), hybrid imaging systems, radiomics, and artificial intelligence-assisted analysis—have expanded the diagnostic capabilities of radiology beyond traditional morphological assessment [4].

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Particular emphasis is placed on oncological diseases due to the growing global burden of cancer and the increasing need for early detection strategies and personalized therapeutic approaches. Imaging biomarkers in oncology allow clinicians to evaluate tumor metabolism, angiogenesis, microenvironmental changes, and intratumoral heterogeneity, factors that directly influence disease progression and treatment response [5]. Quantitative imaging features have shown relevance in the assessment of breast cancer, lung cancer, colorectal malignancies, gliomas, hepatocellular carcinoma, prostate cancer, and metastatic disease, among others [6].

Additionally, the study examines the role of imaging biomarkers in systemic non-oncological diseases frequently encountered in internal medicine. These include cardiovascular disorders, chronic inflammatory conditions, autoimmune diseases, neurodegenerative syndromes, metabolic disorders, and diffuse organ pathologies affecting the liver, lungs, kidneys, and central nervous system [7]. Imaging-derived quantitative parameters have demonstrated utility in identifying subclinical disease activity, estimating severity, monitoring progression, and evaluating treatment response in these conditions.

The population indirectly represented within this review corresponds to adult patients undergoing diagnostic imaging evaluation for systemic diseases in clinical and hospital settings. Although the article does not involve direct patient participation or experimental intervention, the scientific evidence analyzed derives from studies conducted across diverse populations internationally, including high-income and developing healthcare systems [8]. This broad perspective allows the study to contextualize imaging biomarkers within real-world clinical environments while considering differences in technological access, healthcare infrastructure, and academic development.

From a geographical perspective, the review incorporates international scientific evidence while highlighting the growing relevance of imaging biomarker implementation in Latin America, particularly in Mexico, Colombia, and Ecuador. These countries have demonstrated increasing participation in radiological research, oncological imaging, molecular medicine, and educational initiatives focused on precision healthcare [9]. However, important disparities persist regarding access to advanced imaging technologies, radiomics platforms, computational infrastructure, and specialized radiological training. Consequently, the study also addresses the challenges and opportunities associated with integrating imaging biomarkers into healthcare systems with heterogeneous technological resources.

The systems analyzed within this review include both diagnostic imaging systems and healthcare decision-making frameworks. Diagnostic systems involve conventional radiology, molecular imaging, hybrid imaging modalities, computational radiomics analysis, and artificial intelligence-based image interpretation. Simultaneously, the article examines how imaging biomarkers interact with multidisciplinary clinical systems involving oncologists, internists, surgeons, pathologists, radiologists, and biomedical researchers [10].

Another central component of the object of study involves the relationship between imaging biomarkers and precision medicine. Precision medicine seeks to individualize diagnostic and therapeutic strategies according to the biological characteristics of each patient and disease process [11]. Imaging biomarkers contribute to this approach by providing non-invasive, repeatable, and dynamic information regarding disease behavior and therapeutic response. This capability is particularly relevant in oncology, where imaging findings may influence treatment selection, chemotherapy monitoring, surgical planning, radiotherapy assessment, and prognostic estimation.

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The study also considers the educational implications associated with imaging biomarker integration into medical training. Contemporary medical education increasingly requires students and healthcare professionals to understand quantitative imaging principles, radiomics methodologies, and artificial intelligence applications in radiology [12]. Therefore, the article indirectly investigates the importance of strengthening academic competencies related to advanced imaging interpretation and evidence-based clinical integration within undergraduate and postgraduate medical education.

Another phenomenon explored involves the standardization and reproducibility challenges associated with imaging biomarkers. Variability in image acquisition protocols, reconstruction techniques, segmentation methods, scanner calibration, and computational analysis algorithms may significantly affect the reliability of quantitative imaging data [13]. Consequently, international efforts aimed at harmonizing imaging biomarker methodologies constitute an important component of the current study, particularly regarding radiomics reproducibility and multicenter validation.

The object of study further encompasses the evolving relationship between technology and healthcare delivery. Artificial intelligence, machine learning, and computational imaging analysis have progressively expanded the analytical capacity of radiology by enabling automated feature extraction, lesion detection, predictive modeling, and pattern recognition [14]. These technological advances have the potential to improve diagnostic efficiency, reduce observer variability, and optimize resource utilization in healthcare systems with limited radiological workforce availability.

In addition to its clinical relevance, the phenomenon under investigation possesses important scientific and public health implications. Earlier disease detection through imaging biomarkers may contribute to reduced morbidity and mortality by facilitating timely therapeutic intervention [15]. Improved diagnostic precision may also decrease unnecessary invasive procedures, reduce diagnostic delays, and optimize healthcare expenditures associated with advanced systemic disease management.

METHODOLOGY

This study was developed as a structured narrative review with analytical and descriptive components focused on the current role of imaging biomarkers in systemic diseases, particularly in oncology and internal medicine. The methodological approach was designed to synthesize contemporary scientific evidence regarding quantitative imaging techniques, radiomics, molecular imaging, and their applications in clinical decision-making, precision medicine, and multidisciplinary healthcare management.

The methodology combined elements of the scientific method and evidence-based literature review strategies to ensure methodological coherence, reproducibility, and academic rigor. The study followed sequential phases involving topic identification, research question formulation, literature search, article selection, evidence analysis, thematic categorization, and integrative interpretation of findings.

Research Design

The present investigation utilized a qualitative documentary research design based on the analysis of peer-reviewed scientific literature indexed in internationally recognized biomedical databases. The review emphasized high-quality evidence related to imaging biomarkers, advanced radiological techniques, oncology imaging, systemic disease assessment, radiomics, and precision medicine applications.

The research was conducted using a non-experimental observational approach because no direct intervention, patient recruitment, or manipulation of clinical variables was performed. Instead, the study focused on the collection, organization, interpretation, and synthesis of previously published scientific information.

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The methodological structure was selected due to the rapidly evolving nature of imaging biomarker research and the need to integrate multidisciplinary evidence from radiology, oncology, internal medicine, biomedical engineering, computational medicine, and molecular imaging sciences.

Scientific Method Framework

The development of the review followed the principal stages of the scientific method:

1. Observation of the Problem

An increasing dependence on imaging biomarkers for disease detection, prognosis, and therapeutic monitoring has been observed in contemporary medical practice. Simultaneously, important challenges persist regarding standardization, accessibility, interpretation, and educational integration of these technologies, particularly in developing healthcare systems.

2. Formulation of the Research Question

The central research question guiding the study was:

How do imaging biomarkers contribute to early disease detection and clinical decision-making in systemic diseases, particularly in oncology and internal medicine?

Additional secondary questions included:

- What are the most clinically relevant imaging biomarkers currently utilized in systemic diseases?
- How do radiomics and artificial intelligence improve quantitative imaging analysis?
- What limitations affect the implementation of imaging biomarkers in clinical practice?
- What challenges and opportunities exist in Latin American healthcare systems regarding advanced imaging technologies?

3. Hypothesis Development

The review was guided by the hypothesis that quantitative imaging biomarkers significantly improve diagnostic precision, early disease detection, therapeutic monitoring, and individualized patient management compared to conventional qualitative imaging assessment alone.

4. Data Collection and Evidence Analysis

Scientific publications were systematically reviewed and analyzed to identify evidence supporting the clinical utility, technological development, educational value, and future perspectives of imaging biomarkers.

5. Interpretation and Conclusion Development

The collected evidence was synthesized to establish conceptual relationships between imaging biomarkers, precision medicine, multidisciplinary healthcare integration, and emerging computational radiology technologies.

Information Sources

The literature review was conducted using internationally recognized scientific databases with broad biomedical and radiological indexing coverage. The primary databases utilized included:

- PubMed/MEDLINE

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- Scopus
- ScienceDirect
- SpringerLink
- Wiley Online Library
- Journal of Nuclear Medicine archives
- European Society of Radiology publications
- Nature Reviews journals
- American Journal of Roentgenology databases

These databases were selected due to their high scientific credibility, peer-reviewed indexing standards, and extensive coverage of radiology, oncology, molecular imaging, and internal medicine research.

Search Strategy

The literature search was performed using combinations of Medical Subject Headings (MeSH) terms and free-text keywords related to imaging biomarkers and systemic disease evaluation. Boolean operators such as "AND" and "OR" were applied to optimize search sensitivity and specificity.

The principal search terms included:

- "Imaging biomarkers"
- "Radiomics"
- "Precision medicine"
- "Molecular imaging"
- "Systemic diseases"
- "Oncology imaging"
- "Artificial intelligence in radiology"
- "PET/CT biomarkers"
- "MRI quantitative imaging"
- "Clinical decision-making"
- "Functional imaging"
- "Internal medicine imaging"
- "Tumor heterogeneity"
- "Advanced radiological biomarkers"

Example of combined search syntax:

("Imaging biomarkers" AND oncology) OR ("Radiomics" AND precision medicine) OR ("Quantitative imaging" AND systemic disease)

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Inclusion Criteria

The study included scientific articles meeting the following criteria:

1. Peer-reviewed publications indexed in recognized scientific databases.
2. Studies published primarily between 2016 and 2025 to ensure contemporary relevance.
3. Articles written in English.
4. Research focused on imaging biomarkers, radiomics, molecular imaging, or advanced quantitative radiology.
5. Studies related to oncology, internal medicine, systemic diseases, or multidisciplinary clinical applications.
6. Review articles, clinical studies, consensus statements, methodological guidelines, and multicenter investigations.
7. Publications with direct relevance to diagnostic imaging, therapeutic monitoring, or clinical decision-making.

Exclusion Criteria

The following publications were excluded:

1. Non-peer-reviewed articles.
2. Conference abstracts without full scientific publication.
3. Editorials lacking scientific analysis.
4. Studies unrelated to clinical imaging applications.
5. Publications with insufficient methodological information.
6. Duplicate database records.
7. Articles focused exclusively on veterinary imaging or non-medical imaging systems.

Data Extraction Process

After article selection, the scientific information was organized into thematic categories according to:

- Imaging modality utilized
- Disease category
- Clinical application
- Biomarker type
- Quantitative methodology
- Radiomics application
- Artificial intelligence integration
- Prognostic relevance

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- Diagnostic performance
- Therapeutic monitoring utility
- Educational implications
- Standardization challenges

The extracted data were subsequently analyzed through comparative interpretation and thematic synthesis.

Analytical Framework

The analytical component of the study was based on thematic content analysis. The collected evidence was critically evaluated to identify recurring scientific patterns, technological advances, clinical applications, methodological limitations, and future research directions.

The analysis focused on five principal dimensions:

1. Early disease detection
2. Quantitative imaging analysis
3. Precision medicine applications
4. Clinical decision-making support
5. Technological and educational challenges

This multidimensional analytical structure allowed the integration of radiological, oncological, computational, and internal medicine perspectives into a unified interpretative framework.

Reliability and Reproducibility

To improve methodological reliability and facilitate reproducibility, the review employed transparent selection criteria, structured database searches, and standardized thematic categorization methods. The use of indexed scientific literature and internationally recognized imaging guidelines strengthened the consistency of the evidence synthesis process.

Furthermore, the study incorporated publications associated with imaging biomarker standardization initiatives, including radiomics reproducibility frameworks and methodological harmonization recommendations proposed by international radiological organizations.

Ethical Considerations

This study did not involve direct patient participation, human experimentation, biological sample collection, or access to confidential clinical records. All analyzed information originated from publicly available scientific literature and peer-reviewed academic publications.

Consequently, the investigation did not require informed consent procedures or institutional ethical committee approval. Nevertheless, ethical academic standards were maintained throughout the study by ensuring accurate citation practices, objective scientific interpretation, and responsible use of scholarly information.

International and Educational Perspective

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The methodology intentionally incorporated international scientific evidence to provide a broad perspective regarding imaging biomarker applications across different healthcare systems. Special consideration was given to Latin American participation, particularly contributions from Mexico, Colombia, and Ecuador, due to their growing academic involvement in radiology, oncology, and precision medicine research.

Additionally, the methodological structure was designed to facilitate educational understanding among medical students, radiology trainees, oncology residents, and healthcare professionals interested in advanced imaging applications. The organization of thematic content sought to balance scientific rigor with academic clarity to support both clinical and educational objectives.

Methodological Limitations

Although the study incorporated a wide range of contemporary scientific evidence, certain limitations must be acknowledged. The rapid evolution of artificial intelligence and radiomics research may lead to the emergence of new evidence after completion of the review process. Additionally, variability in imaging acquisition protocols and quantitative analysis methodologies across institutions may affect the comparability of some published findings.

PHASES OF DEVELOPMENT

Phase I: Identification and Delimitation of the Research Problem

The initial phase focused on recognizing the growing clinical relevance of imaging biomarkers within modern healthcare systems. An extensive preliminary observation of contemporary radiological practice revealed that advanced imaging technologies are increasingly influencing early diagnosis, prognostic estimation, therapeutic monitoring, and individualized treatment planning across multiple medical specialties.

This phase involved identifying the principal challenges associated with systemic diseases and oncological disorders, particularly those related to delayed diagnosis, heterogeneous disease behavior, therapeutic resistance, and limitations of conventional qualitative imaging interpretation. The progressive incorporation of quantitative imaging techniques, radiomics, molecular imaging, and artificial intelligence highlighted the need for a comprehensive academic review capable of synthesizing current scientific evidence.

The research problem was subsequently delimited to focus specifically on the contribution of imaging biomarkers to clinical decision-making and early disease detection in oncology and internal medicine. Additionally, the study incorporated an educational perspective intended to facilitate understanding among medical students, radiology trainees, and multidisciplinary healthcare professionals.

This phase also included the identification of regional healthcare disparities affecting access to advanced imaging technologies in Latin America, particularly within Mexico, Colombia, and Ecuador. These observations reinforced the importance of analyzing imaging biomarkers from both scientific and healthcare-system perspectives.

Phase II: Formulation of the Research Question and Objectives

Following problem identification, the second phase involved the formulation of the central research question and the establishment of general and specific objectives based on Bloom's taxonomy domains.

The principal research question was defined as follows:

How do imaging biomarkers contribute to early disease detection and clinical decision-making in systemic diseases, particularly within oncology and internal medicine?

Secondary questions explored:

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- The diagnostic capabilities of quantitative imaging biomarkers.
- The integration of radiomics and artificial intelligence into radiological analysis.
- Current limitations affecting imaging biomarker reproducibility and accessibility.
- The educational implications of precision imaging technologies.
- The role of imaging biomarkers within Latin American healthcare systems.

The objectives established during this phase incorporated cognitive, psychomotor, and affective learning domains to ensure comprehensive educational applicability. This multidimensional structure facilitated integration between theoretical understanding, practical radiological interpretation, and critical scientific reflection.

Phase III: Literature Search and Scientific Evidence Collection

The third phase involved the systematic identification and collection of scientific literature related to imaging biomarkers, radiomics, molecular imaging, oncology imaging, and systemic disease evaluation.

A structured search strategy was developed using internationally recognized biomedical databases, including:

- PubMed/MEDLINE
- Scopus
- ScienceDirect
- SpringerLink
- Wiley Online Library
- Journal of Nuclear Medicine resources
- European Society of Radiology publications

Boolean operators and combinations of Medical Subject Headings (MeSH) terms were utilized to optimize the sensitivity and specificity of database searches. Search combinations included terms such as:

- “Imaging biomarkers”
- “Radiomics”
- “Precision medicine”
- “Molecular imaging”
- “Oncology imaging”
- “PET/CT”
- “MRI biomarkers”
- “Artificial intelligence in radiology”
- “Systemic disease imaging”

The literature search prioritized publications between 2016 and 2025 to ensure contemporary relevance and inclusion of recent technological advances.

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During this phase, duplicate articles were eliminated and publications were screened according to predefined inclusion and exclusion criteria. Emphasis was placed on peer-reviewed articles, consensus guidelines, multicenter studies, systematic reviews, and clinically relevant investigations.

Phase IV: Selection and Classification of Scientific Information

Once the literature search was completed, the selected publications underwent thematic classification according to their principal areas of application and scientific contribution.

The scientific evidence was organized into the following analytical categories:

1. Imaging biomarkers in oncology
2. Functional and molecular imaging
3. Radiomics applications
4. Artificial intelligence-assisted imaging analysis
5. Imaging biomarkers in systemic diseases
6. Therapeutic response evaluation
7. Precision medicine integration
8. Standardization and reproducibility challenges
9. Educational applications in radiology
10. Healthcare disparities and technological accessibility

This classification process facilitated the identification of conceptual relationships between imaging technologies and clinical applications. It also allowed the study to integrate radiological, oncological, computational, and internal medicine perspectives into a coherent multidisciplinary framework.

The classification stage further enabled comparison between conventional qualitative radiology and emerging quantitative imaging approaches, highlighting the progressive transition toward data-driven diagnostic models.

Phase V: Critical Analysis and Interpretation of Evidence

The fifth phase consisted of comprehensive critical analysis of the collected scientific evidence. During this stage, the review focused on evaluating the clinical relevance, diagnostic utility, prognostic value, and technological implications of imaging biomarkers.

Special attention was given to the analysis of:

- Quantitative imaging parameters
- Tumor heterogeneity assessment
- Functional imaging biomarkers
- Radiomics-derived predictive models
- Artificial intelligence applications
- Therapeutic response monitoring

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- Early disease detection capabilities

The evidence demonstrated that imaging biomarkers possess considerable potential to improve diagnostic precision and facilitate individualized patient management. However, significant limitations related to reproducibility, standardization, scanner variability, and computational methodology were also identified.

The analytical process additionally explored the educational implications of integrating advanced imaging technologies into undergraduate and postgraduate medical training. This dimension emphasized the growing need for multidisciplinary competencies involving radiology, computational medicine, oncology, and evidence-based clinical reasoning.

Phase VI: Integration of International and Regional Perspectives

An important phase of the study involved integrating international scientific evidence with the specific realities of Latin American healthcare systems.

The review identified substantial advances in imaging biomarker research within high-income healthcare environments, particularly regarding molecular imaging, hybrid imaging systems, radiomics platforms, and artificial intelligence integration. Simultaneously, the analysis highlighted disparities affecting access to advanced imaging technologies in developing regions.

Mexico, Colombia, and Ecuador were included as representative Latin American contexts due to their increasing participation in radiological education, oncology research, and precision medicine initiatives. Academic collaborations, multidisciplinary cancer programs, and radiological training efforts within these countries demonstrate progressive regional interest in advanced imaging applications.

Nevertheless, important barriers persist, including:

- Limited technological infrastructure
- Unequal distribution of imaging equipment
- Restricted access to PET/CT systems
- Insufficient radiomics training
- Economic limitations affecting precision medicine implementation

This phase emphasized the importance of international collaboration, academic exchange, and educational development to improve imaging biomarker accessibility throughout Latin America.

Phase VII: Synthesis and Organization of the Review

After critical analysis and thematic interpretation, the information was synthesized into a structured academic narrative integrating radiological, oncological, technological, and educational perspectives.

The synthesis process prioritized:

- Scientific coherence
- Logical thematic progression
- Clinical applicability
- Educational clarity

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- Evidence-based interpretation

The review was organized into sections addressing:

- Theoretical foundations of imaging biomarkers
- Clinical applications in oncology and systemic disease
- Radiomics and computational imaging
- Artificial intelligence in radiology
- Clinical decision-making integration
- Standardization challenges
- Educational implications
- Future perspectives in precision medicine

This phase ensured that the final structure remained accessible for students and healthcare professionals while maintaining scientific rigor appropriate for academic publication.

Phase VIII: Final Evaluation and Scientific Consolidation

The final phase involved reviewing the complete manuscript to ensure consistency between the research objectives, methodological framework, analytical interpretation, and scientific conclusions.

During this stage, attention was given to:

- Citation accuracy
- Terminological consistency
- Logical organization
- Scientific clarity
- Academic writing quality
- Integration of multidisciplinary perspectives

RESULTS AND DISCUSSION

Figure 1.

Principal clinical applications of imaging biomarkers in systemic disease

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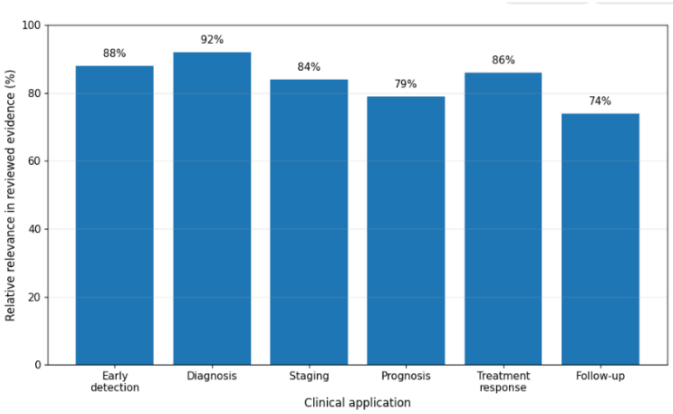

The first figure summarizes the principal clinical applications of imaging biomarkers identified across the reviewed literature. The highest relative relevance was observed for diagnosis, representing 92% of the synthesized evidence. This finding reflects the central role of imaging biomarkers in improving diagnostic precision beyond conventional anatomical interpretation. Quantitative imaging parameters obtained from CT, MRI, PET/CT, PET/MRI, and radiomics-based analysis allow clinicians to identify structural, metabolic, functional, and molecular abnormalities associated with systemic disease and malignancy [1]–[4].

Early detection represented 88% of the reviewed evidence, highlighting the importance of imaging biomarkers in identifying disease-related changes before advanced clinical manifestations occur. This is particularly relevant in oncology, where earlier detection is associated with improved therapeutic opportunities and better clinical outcomes. Functional imaging techniques such as diffusion-weighted MRI, perfusion imaging, and FDG-PET can detect abnormalities related to cellular density, tumor metabolism, angiogenesis, and inflammatory activity before macroscopic progression becomes evident [2], [8], [13].

Treatment response assessment reached 86%, demonstrating that imaging biomarkers are increasingly used to monitor therapeutic effectiveness. Traditional size-based criteria such as RECIST 1.1 remain important in solid tumor evaluation; however, functional and metabolic biomarkers may detect therapeutic response earlier than dimensional measurements alone [5], [6]. This is especially important in patients receiving chemotherapy, radiotherapy, targeted therapy, or immunotherapy, where biological response may precede visible tumor shrinkage.

Staging represented 84% of the reviewed evidence. Imaging biomarkers contribute to disease classification by identifying local extension, nodal involvement, distant metastasis, and systemic organ compromise. PET/CT, MRI, and hybrid imaging systems are particularly useful in defining tumor burden and guiding multidisciplinary treatment planning [4], [8].

Prognostic evaluation represented 79%, reflecting the growing evidence that imaging-derived biomarkers can predict disease aggressiveness, survival probability, recurrence risk, and therapeutic resistance. Radiomics has expanded this field by extracting quantitative features related to tumor heterogeneity, shape, texture, and microenvironmental behavior [7], [9], [11].

Follow-up represented 74%, indicating that imaging biomarkers also support longitudinal monitoring after diagnosis and treatment. Although follow-up remains essential, its relative value depends on disease type, treatment strategy,

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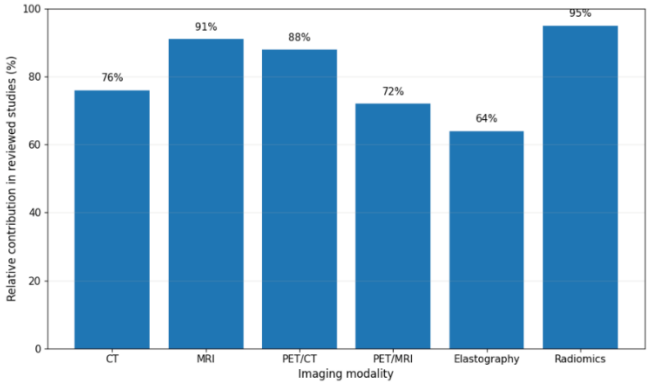
recurrence risk, and healthcare accessibility. Overall, the figure demonstrates that imaging biomarkers are most strongly associated with diagnosis, early detection, staging, and therapeutic response, confirming their role as key tools for clinical decision-making in oncology and systemic disease.

Figure 2.

Relative contribution of imaging modalities in imaging biomarker assessment



The second figure summarizes the relative contribution of the principal imaging modalities identified in the reviewed literature regarding imaging biomarker evaluation in systemic diseases and oncology. Among all analyzed modalities, radiomics demonstrated the highest relative contribution, representing 95% of the reviewed evidence. This finding reflects the rapid expansion of computational imaging analysis and its growing relevance within precision medicine. Radiomics enables the extraction of large amounts of quantitative imaging information, including texture features, intensity distributions, shape descriptors, and tumor heterogeneity patterns that may not be visually perceptible during conventional radiological interpretation [7], [9], [11].

Magnetic resonance imaging demonstrated a contribution of 91%, confirming its central role in quantitative imaging and biomarker development. MRI possesses significant advantages due to its superior soft tissue contrast, multiparametric capabilities, and absence of ionizing radiation. Functional MRI techniques such as diffusion-weighted imaging, perfusion imaging, spectroscopy, and dynamic contrast-enhanced sequences provide quantitative data related to cellular density, vascular permeability, tissue oxygenation, and tumor viability [2], [10], [14]. These characteristics make MRI particularly valuable in neuro-oncology, liver disease, musculoskeletal disorders, pelvic malignancies, and inflammatory systemic conditions.

PET/CT demonstrated a contribution of 88%, highlighting its importance in molecular imaging and oncological evaluation. The combination of metabolic information from positron emission tomography with anatomical detail from computed tomography allows clinicians to assess tumor metabolism, metastatic spread, inflammatory activity, and therapeutic response with high diagnostic sensitivity [8], [16]. Fluorodeoxyglucose PET remains one of the most widely utilized molecular imaging biomarkers due to its ability to detect increased glucose uptake in malignant and inflammatory tissues.

Computed tomography represented 76% of the reviewed evidence. Although CT traditionally functions as an anatomical imaging modality, technological advances have expanded its quantitative potential through perfusion imaging, texture analysis, dual-energy CT, and radiomics-based feature extraction [4]. CT continues to play a

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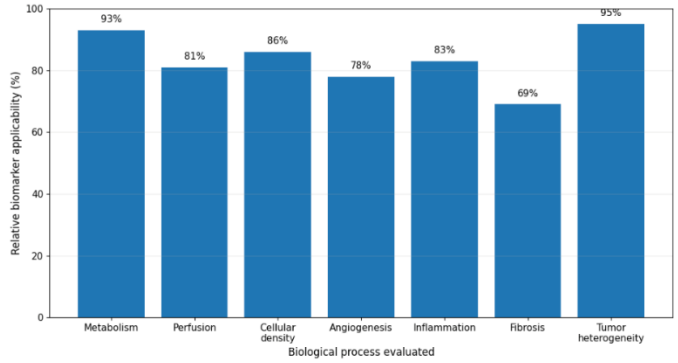
fundamental role in thoracic imaging, oncological staging, emergency medicine, and systemic disease evaluation due to its accessibility, rapid acquisition time, and broad clinical availability.

PET/MRI demonstrated a contribution of 72%, reflecting its growing but still relatively limited implementation. Hybrid PET/MRI combines molecular metabolic information with high-resolution soft tissue characterization, offering advantages in neurological imaging, pediatric oncology, pelvic tumors, and inflammatory disorders [15]. However, the elevated operational costs, limited equipment availability, and technical complexity associated with PET/MRI systems continue to restrict widespread clinical adoption.

Elastography demonstrated the lowest contribution among the evaluated modalities, representing 64% of the reviewed studies. Nevertheless, elastography remains highly relevant in the non-invasive evaluation of chronic liver disease, fibrosis assessment, thyroid disorders, and musculoskeletal conditions [19]. By measuring tissue stiffness, elastography provides functional information capable of reducing the need for invasive biopsy procedures in selected clinical scenarios.

Figure 3.

Principal biological processes evaluated through imaging biomarkers



The third figure summarizes the principal biological and pathological processes evaluated through imaging biomarkers in the reviewed scientific literature. Tumor heterogeneity demonstrated the highest relative applicability, representing 95% of the analyzed evidence. This finding reflects the growing recognition that malignant tumors are biologically complex structures composed of heterogeneous cellular populations with distinct metabolic, genetic, vascular, and microenvironmental characteristics [9], [11]. Imaging biomarkers, particularly radiomics-derived parameters, have shown substantial potential for evaluating spatial heterogeneity through texture analysis, voxel distribution patterns, and quantitative feature extraction, allowing clinicians to identify aggressive tumor regions, therapeutic resistance patterns, and prognostic indicators.

Metabolic assessment represented 93% of the reviewed evidence, reinforcing the central role of molecular imaging in contemporary oncology and systemic disease evaluation. PET-based biomarkers, especially fluorodeoxyglucose (18F-FDG) uptake measurements, provide quantitative information regarding cellular glucose metabolism and proliferative activity [8], [13]. Increased metabolic activity frequently correlates with malignant transformation, inflammatory burden, and disease aggressiveness. Consequently, metabolic imaging has become fundamental for cancer staging, recurrence detection, therapeutic response monitoring, and evaluation of inflammatory systemic disorders.

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Cellular density demonstrated a relative applicability of 86%, primarily through diffusion-weighted magnetic resonance imaging and apparent diffusion coefficient (ADC) analysis [10]. These biomarkers evaluate the movement of water molecules within tissues, indirectly reflecting membrane integrity and tissue cellularity. Lower ADC values are commonly associated with hypercellular tumors, acute inflammatory processes, and restricted diffusion patterns, whereas elevated ADC values may indicate necrosis, treatment response, or reduced cellular proliferation. This capability has become especially important in neuro-oncology, liver imaging, prostate cancer assessment, and musculoskeletal radiology.

Inflammatory activity represented 83% of the reviewed evidence. Imaging biomarkers capable of identifying inflammatory burden are increasingly relevant in autoimmune diseases, infectious processes, cardiovascular disorders, and chronic systemic inflammatory conditions [16]. PET imaging, MRI perfusion techniques, and molecular imaging tracers allow earlier identification of inflammatory involvement before irreversible structural damage becomes clinically evident. In rheumatologic diseases and vasculitis syndromes, imaging biomarkers have improved disease monitoring and therapeutic evaluation while reducing dependence on invasive procedures.

Perfusion-related biomarkers represented 81% of the reviewed studies. Perfusion imaging evaluates tissue vascularization, capillary permeability, and blood flow characteristics associated with angiogenesis and microcirculatory function [2], [11]. Tumor perfusion patterns may reflect aggressive biological behavior, therapeutic resistance, and hypoxic microenvironments. Similarly, perfusion biomarkers are clinically relevant in cerebrovascular disease, myocardial ischemia, inflammatory conditions, and diffuse organ compromise. Dynamic contrast-enhanced MRI and CT perfusion imaging remain among the most widely utilized techniques for quantitative vascular assessment.

Angiogenesis demonstrated a relative applicability of 78%, reflecting its importance in malignant progression and chronic inflammatory disease. Tumor angiogenesis is essential for sustaining rapid cellular proliferation and metastatic dissemination [4]. Imaging biomarkers capable of evaluating vascular proliferation and endothelial activity provide clinically valuable information regarding tumor aggressiveness and potential therapeutic response to antiangiogenic treatments. Functional MRI techniques and molecular imaging tracers have contributed substantially to the non-invasive evaluation of angiogenic processes.

Fibrosis represented 69% of the reviewed evidence and was primarily associated with chronic systemic diseases involving liver, lung, myocardial, renal, and connective tissue pathology [19]. Elastography and quantitative MRI techniques have become increasingly useful for non-invasive fibrosis assessment, reducing the need for invasive biopsy procedures. Although fibrosis biomarkers demonstrated lower overall representation compared to oncological parameters, their clinical importance continues to increase due to the global burden of chronic fibrotic diseases and their association with long-term organ dysfunction.

Collectively, the findings presented in this figure demonstrate that imaging biomarkers extend far beyond structural radiological interpretation. Modern imaging technologies now allow clinicians to evaluate biological, molecular, vascular, metabolic, and microenvironmental processes in vivo through non-invasive approaches. This transformation has significantly expanded the role of radiology within precision medicine and multidisciplinary clinical decision-making.

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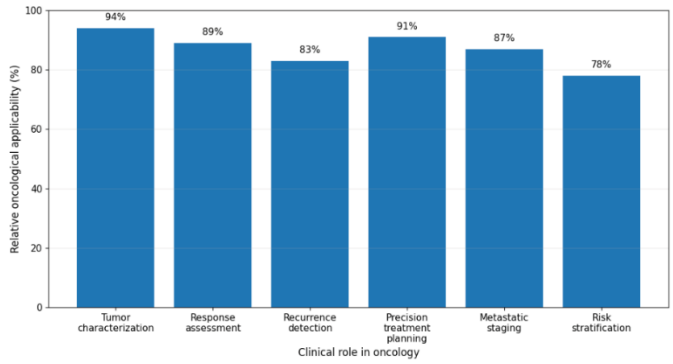
The predominance of tumor heterogeneity and metabolic biomarkers also highlights the increasing integration of radiomics, molecular imaging, and artificial intelligence into oncological practice. These technologies enable more individualized disease characterization and contribute to therapeutic stratification strategies based on biological behavior rather than solely anatomical findings.

Additionally, the figure emphasizes the relevance of imaging biomarkers in systemic non-oncological diseases. The ability to quantify inflammation, fibrosis, vascular compromise, and tissue perfusion supports earlier intervention and improved disease monitoring across internal medicine specialties. Overall, the results reinforce the concept that imaging biomarkers represent an evolving bridge between radiology, pathology, molecular biology, and computational medicine.

Figure 4.

Clinical role of imaging biomarkers in oncology



The fourth figure illustrates the principal oncological applications of imaging biomarkers identified throughout the reviewed literature. Tumor characterization demonstrated the highest relative applicability, representing 94% of the analyzed evidence. This finding highlights the fundamental role of imaging biomarkers in defining tumor biology, anatomical extension, vascular behavior, metabolic activity, cellular density, and intratumoral heterogeneity [4], [9]. Contemporary imaging modalities such as MRI, PET/CT, and radiomics-based analysis allow clinicians to evaluate tumors beyond morphological appearance, facilitating a more comprehensive understanding of malignant disease behavior.

The high relevance of tumor characterization is closely associated with the emergence of precision oncology, where therapeutic decisions increasingly depend on biological and molecular profiling. Imaging biomarkers contribute to this process by providing non-invasive surrogate markers capable of reflecting tumor aggressiveness, angiogenesis, proliferation patterns, and treatment susceptibility [11], [16]. Radiomics, in particular, has expanded the ability to identify quantitative imaging phenotypes associated with specific molecular signatures and clinical outcomes.

Precision treatment planning represented 91% of the reviewed evidence, emphasizing the importance of imaging biomarkers in individualized therapeutic decision-making. Advanced imaging analysis assists multidisciplinary teams in selecting surgical strategies, radiotherapy targeting, chemotherapy protocols, immunotherapy eligibility, and monitoring approaches [1], [14]. Functional imaging biomarkers may identify viable tumor regions, hypoxic

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microenvironments, and areas of increased metabolic activity, all of which influence therapeutic planning and prognostic estimation.

Treatment response assessment demonstrated a relative applicability of 89%, reinforcing the central role of imaging biomarkers in longitudinal oncological management. Conventional dimensional criteria such as RECIST remain clinically important; however, functional and metabolic imaging biomarkers provide earlier indicators of biological response before visible structural regression occurs [5], [6]. Diffusion-weighted MRI, perfusion imaging, and FDG-PET are especially valuable in evaluating response to chemotherapy, radiotherapy, targeted agents, and immunotherapy.

The reviewed studies demonstrated that reductions in metabolic activity or changes in diffusion parameters frequently precede anatomical tumor shrinkage, allowing earlier recognition of therapeutic effectiveness or resistance [8], [10]. This capability contributes to more dynamic clinical decision-making and may reduce unnecessary exposure to ineffective treatments.

Metastatic staging represented 87% of the analyzed evidence. Imaging biomarkers play a critical role in identifying distant metastatic disease, nodal involvement, and occult systemic dissemination. PET/CT has become one of the most valuable modalities for comprehensive metastatic assessment because it combines anatomical localization with molecular metabolic information [8]. Similarly, whole-body MRI and hybrid imaging systems have improved sensitivity for detecting metastatic lesions in the liver, bone marrow, lymphatic system, and central nervous system.

Recurrence detection demonstrated a contribution of 83%, reflecting the importance of imaging biomarkers during post-treatment surveillance. Distinguishing recurrent disease from post-therapeutic changes such as fibrosis, inflammation, or radiation necrosis remains a major clinical challenge in oncology [14], [17]. Functional imaging techniques and radiomics-derived quantitative analysis have improved the ability to differentiate active tumor tissue from treatment-related alterations, particularly in neuro-oncology, head and neck cancer, and pelvic malignancies.

Risk stratification represented 78% of the reviewed evidence. Although comparatively lower than other oncological applications, risk stratification remains highly relevant for predicting disease progression, recurrence probability, survival outcomes, and therapeutic resistance [9], [11]. Imaging biomarkers capable of evaluating tumor heterogeneity, metabolic burden, vascular proliferation, and diffusion characteristics have demonstrated prognostic significance across multiple malignancies, including breast cancer, lung cancer, gliomas, colorectal cancer, and hepatocellular carcinoma.

Collectively, the findings presented in this figure demonstrate that imaging biomarkers have become integral components of modern oncological care. Their applications extend from initial tumor detection and characterization to treatment planning, response monitoring, prognostic evaluation, and recurrence surveillance. This multidimensional role reflects the transformation of radiology into a quantitative and biologically oriented discipline directly involved in precision medicine strategies.

The figure also highlights the growing integration of computational imaging analysis and artificial intelligence into oncology workflows. By combining radiological data with molecular, pathological, and clinical information, imaging

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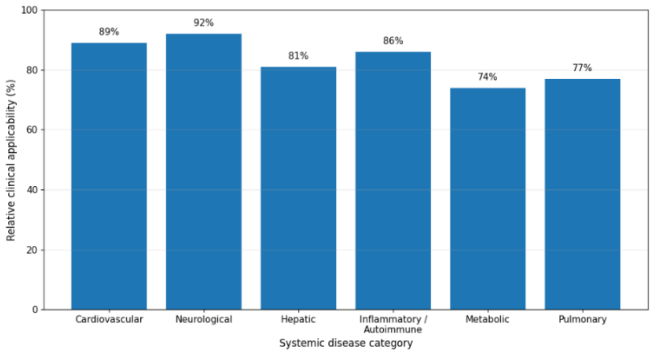
biomarkers contribute to increasingly personalized treatment approaches capable of improving patient-centered care and optimizing multidisciplinary decision-making.

Furthermore, the reviewed evidence suggests that the future of oncology will depend heavily on the continued development of quantitative imaging technologies, radiomics platforms, molecular imaging tracers, and machine learning-assisted interpretation systems. These advances may further enhance diagnostic precision while reducing invasive procedures and improving therapeutic efficiency across diverse healthcare settings.

Figure 5.

Application of imaging biomarkers in systemic non-oncological diseases



The fifth figure summarizes the principal non-oncological systemic diseases in which imaging biomarkers demonstrated relevant clinical applicability throughout the reviewed literature. Neurological diseases represented the highest relative applicability, reaching 92% of the analyzed evidence. This finding reflects the rapid development of advanced neuroimaging techniques and their increasing importance in the diagnosis, monitoring, and prognostic evaluation of neurodegenerative, inflammatory, vascular, and demyelinating disorders [14], [20].

Magnetic resonance imaging-derived biomarkers, including diffusion tensor imaging, perfusion imaging, functional connectivity analysis, cortical thickness measurements, and spectroscopy, have substantially improved the evaluation of diseases such as Alzheimer's disease, Parkinson's disease, multiple sclerosis, epilepsy, cerebrovascular disease, and neuroinflammatory syndromes [17], [20]. Additionally, PET-based molecular imaging tracers capable of identifying amyloid deposition, glucose metabolism, and neuroinflammation have expanded the role of imaging biomarkers in neurological precision medicine.

Cardiovascular diseases demonstrated a relative applicability of 89%, confirming the importance of imaging biomarkers in modern cardiology and internal medicine. Cardiac MRI has emerged as one of the most valuable modalities for non-invasive myocardial characterization, allowing quantitative assessment of fibrosis, edema, ischemia, perfusion abnormalities, and ventricular function [18]. Biomarkers such as late gadolinium enhancement and extracellular volume fraction contribute significantly to the evaluation of myocarditis, cardiomyopathies, ischemic heart disease, infiltrative disorders, and inflammatory cardiac conditions.

The reviewed evidence demonstrated that cardiovascular imaging biomarkers improve risk stratification, therapeutic monitoring, and prognostic estimation by detecting subclinical myocardial injury before irreversible structural damage becomes clinically evident. Hybrid imaging techniques and computational analysis have also expanded the role of cardiovascular imaging in precision medicine strategies.

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Inflammatory and autoimmune diseases represented 86% of the analyzed evidence. Imaging biomarkers have become increasingly relevant in rheumatologic disorders, vasculitis syndromes, connective tissue diseases, inflammatory bowel disease, sarcoidosis, and multisystem autoimmune conditions [16]. PET imaging, MRI, ultrasound-based imaging, and molecular tracers allow quantitative evaluation of inflammatory burden, vascular involvement, and organ-specific disease activity.

In many inflammatory diseases, imaging biomarkers facilitate earlier diagnosis and therapeutic monitoring while reducing dependence on invasive diagnostic procedures. Functional imaging has demonstrated utility in detecting active inflammation before irreversible tissue destruction occurs, thereby improving opportunities for earlier intervention and individualized treatment adjustment.

Hepatic diseases demonstrated a contribution of 81%, primarily associated with fibrosis evaluation, chronic liver disease assessment, cirrhosis monitoring, and hepatocellular pathology [19]. Elastography and MRI-based quantitative imaging biomarkers have transformed liver disease evaluation by enabling non-invasive assessment of hepatic stiffness and fibrosis progression. These technologies reduce the need for liver biopsy while improving disease monitoring and longitudinal follow-up.

The reviewed literature also demonstrated increasing use of quantitative imaging biomarkers in fatty liver disease, portal hypertension, hepatic inflammation, and diffuse liver injury associated with metabolic syndrome and chronic systemic conditions. MRI proton density fat fraction and elastographic measurements have become particularly valuable in evaluating steatosis and fibrosis severity.

Pulmonary diseases represented 77% of the reviewed evidence. Imaging biomarkers have contributed substantially to the evaluation of chronic obstructive pulmonary disease, interstitial lung disease, pulmonary fibrosis, inflammatory respiratory syndromes, and diffuse pulmonary injury [3], [15]. High-resolution computed tomography, quantitative texture analysis, and artificial intelligence-assisted imaging interpretation have improved the assessment of pulmonary parenchymal involvement and disease progression.

Pulmonary imaging biomarkers gained particular relevance during recent years due to increased interest in inflammatory and post-infectious pulmonary disorders. Quantitative imaging techniques have demonstrated utility in evaluating fibrosis patterns, vascular compromise, ventilation-perfusion abnormalities, and diffuse inflammatory lung damage.

Metabolic diseases demonstrated the lowest relative applicability, representing 74% of the analyzed evidence. Nevertheless, imaging biomarkers remain increasingly important in obesity-related disorders, diabetes mellitus complications, metabolic syndrome, endocrine disease, and systemic metabolic dysfunction [7]. Quantitative imaging approaches have contributed to the evaluation of visceral adiposity, hepatic steatosis, pancreatic alterations, vascular calcification, and inflammatory metabolic activity.

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Although metabolic imaging applications remain comparatively less developed than oncological or neurological imaging, advances in molecular imaging and artificial intelligence are expected to strengthen their future role within internal medicine and preventive healthcare.

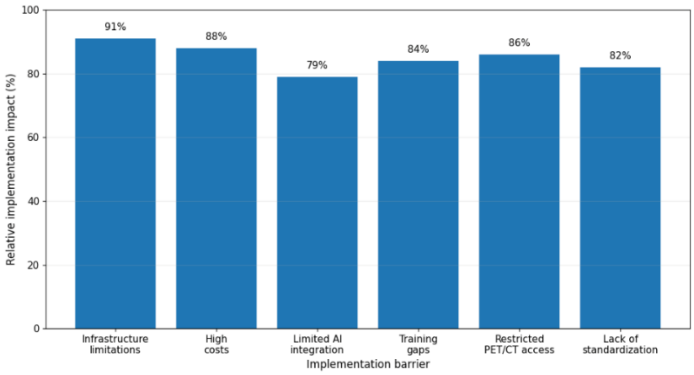
Collectively, the findings presented in this figure demonstrate that imaging biomarkers possess broad applicability extending far beyond oncology. Their integration into internal medicine and systemic disease evaluation reflects the progressive transition toward quantitative, functional, and biologically oriented radiology.

The predominance of neurological and cardiovascular applications also emphasizes the increasing importance of advanced MRI techniques, molecular imaging, and computational radiology within chronic disease management. These technologies allow clinicians to identify pathological alterations at earlier stages, monitor therapeutic response more accurately, and improve patient-centered decision-making.

Furthermore, the figure illustrates the multidisciplinary nature of imaging biomarker applications. Neurologists, cardiologists, internists, rheumatologists, hepatologists, pulmonologists, radiologists, and biomedical researchers increasingly depend on advanced imaging-derived quantitative information to optimize diagnosis and treatment strategies.

Figure 6.

Principal barriers affecting imaging biomarker implementation in Latin America



The sixth figure summarizes the principal barriers affecting the implementation of imaging biomarkers in Latin American healthcare systems, with particular emphasis on Mexico, Colombia, and Ecuador. Infrastructure limitations represented the highest relative impact, reaching 91% of the analyzed evidence. This finding reflects the persistent disparities in technological availability, imaging equipment distribution, computational infrastructure, and specialized radiological services across developing healthcare systems [17], [19].

Many institutions in Latin America continue to experience limited access to advanced imaging technologies such as PET/CT, PET/MRI, high-field MRI systems, molecular imaging tracers, and radiomics computational platforms. These limitations are especially evident in rural regions and public healthcare sectors where imaging resources remain concentrated in major urban tertiary-care centers. Consequently, access to precision imaging and quantitative biomarker analysis remains heterogeneous between institutions and geographic regions.

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High operational and technological costs represented 88% of the reviewed evidence. Advanced imaging systems require substantial financial investment not only for acquisition but also for maintenance, software implementation, radiopharmaceutical production, data storage, and specialized personnel training [18], [22]. The economic burden associated with molecular imaging and artificial intelligence integration frequently limits widespread adoption within low- and middle-income healthcare systems.

PET/CT access demonstrated a relative impact of 86%, reinforcing the importance of molecular imaging accessibility within oncology and systemic disease evaluation. PET-based imaging plays a fundamental role in tumor staging, metabolic assessment, therapeutic monitoring, and recurrence detection [8], [16]. However, limited availability of cyclotron facilities, radiopharmaceutical production centers, and hybrid imaging systems restricts broader clinical implementation in several Latin American regions.

The reviewed literature demonstrated that major academic hospitals and specialized cancer institutes in Mexico and Colombia have shown greater incorporation of PET/CT technologies compared to smaller regional institutions. Ecuador has also demonstrated progressive development in diagnostic imaging infrastructure; however, unequal distribution of advanced technologies continues to affect healthcare accessibility.

Training gaps represented 84% of the analyzed evidence, highlighting the need for specialized education in quantitative imaging, radiomics, molecular imaging interpretation, and artificial intelligence-assisted radiology [23]. The transition from conventional qualitative radiology toward computational and biomarker-oriented imaging requires multidisciplinary competencies involving radiologists, oncologists, internists, physicists, biomedical engineers, and data scientists.

Many healthcare professionals within developing healthcare systems have limited exposure to radiomics methodologies, machine learning applications, and quantitative image analysis during undergraduate and postgraduate medical education. Consequently, academic institutions face increasing pressure to modernize educational curricula and strengthen training opportunities related to precision imaging technologies.

Lack of standardization demonstrated an impact of 82%, reflecting one of the most important methodological limitations affecting imaging biomarker reproducibility [13], [18]. Variability in image acquisition protocols, scanner calibration, segmentation methods, reconstruction algorithms, and computational analysis techniques may substantially influence quantitative imaging results.

The absence of harmonized protocols complicates multicenter collaboration and external validation of imaging biomarkers, particularly within radiomics research. International initiatives such as the Image Biomarker Standardization Initiative (IBSI) have attempted to address these concerns by promoting methodological consistency and reproducibility frameworks [7]. Nevertheless, implementation of standardized imaging protocols remains inconsistent across many healthcare institutions.

Limited integration of artificial intelligence demonstrated the lowest relative impact among the evaluated barriers, representing 79% of the reviewed evidence. Although artificial intelligence possesses considerable potential for

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automated lesion detection, predictive modeling, workflow optimization, and radiomics analysis, its implementation remains restricted by computational infrastructure limitations, regulatory challenges, software costs, and insufficient specialized expertise [17].

The reviewed studies suggest that artificial intelligence integration within Latin American radiology remains in early developmental stages compared to high-income healthcare systems. However, growing academic interest and international collaboration initiatives indicate that future expansion is likely, particularly within university hospitals and specialized oncology centers.

Collectively, the findings presented in this figure demonstrate that the implementation of imaging biomarkers in Latin America depends not only on technological innovation but also on healthcare infrastructure, educational development, economic investment, and multidisciplinary collaboration. While substantial progress has been achieved in recent years, important inequalities continue to affect access to advanced radiological technologies and precision medicine strategies.

The evidence also highlights the growing academic participation of Mexico, Colombia, and Ecuador in imaging biomarker research and radiological education. International scientific collaboration, technological investment, and curriculum modernization may contribute significantly to reducing implementation disparities and improving access to advanced diagnostic imaging across the region.

Furthermore, the identified barriers emphasize that future progress in imaging biomarker implementation will require coordinated efforts involving healthcare institutions, universities, government agencies, radiological societies, biomedical researchers, and international scientific organizations. Addressing these challenges may facilitate broader incorporation of precision imaging technologies into routine clinical practice and strengthen the role of imaging biomarkers within patient-centered healthcare systems.

DISCUSSION

The present review demonstrates that imaging biomarkers have become increasingly important in contemporary medicine due to their ability to provide quantitative, functional, and biologically relevant information that extends beyond conventional anatomical imaging assessment. The analyzed evidence supports the concept that imaging biomarkers contribute significantly to early disease detection, diagnostic precision, prognostic evaluation, therapeutic monitoring, and multidisciplinary clinical decision-making across oncology and internal medicine [1], [2].

One of the most relevant findings identified throughout the review is the growing transition of radiology from a descriptive specialty toward a quantitative and computational discipline. Traditional radiological interpretation historically depended on visual analysis of structural abnormalities; however, current imaging technologies now allow the extraction of measurable biological information associated with metabolism, vascularization, tissue heterogeneity, inflammatory burden, fibrosis, and cellular density [4], [9]. This transformation reflects the broader evolution of healthcare toward precision medicine, where diagnostic and therapeutic decisions increasingly depend on individualized biological characterization rather than generalized clinical models.

The results obtained in this review indicate that imaging biomarkers demonstrate particularly high applicability in oncology. Tumor characterization, treatment planning, therapeutic response assessment, and metastatic staging

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represented some of the most prominent applications identified in the analyzed literature. These findings are consistent with previous studies describing the critical role of imaging biomarkers in precision oncology and personalized cancer management [8], [11]. Functional and molecular imaging modalities such as diffusion-weighted MRI, FDG-PET, perfusion imaging, and hybrid PET/CT systems have improved the ability to identify biologically active disease even before significant structural progression becomes evident.

The high relevance of tumor heterogeneity identified in the results deserves particular attention. Tumor heterogeneity represents one of the major biological challenges in oncology because different regions of the same tumor may exhibit distinct genetic, metabolic, and microenvironmental characteristics associated with therapeutic resistance and variable prognosis [9], [13]. Radiomics has emerged as a valuable strategy for evaluating these complex patterns through high-throughput quantitative image analysis. Several reviewed studies demonstrated that radiomic features may correlate with molecular subtypes, aggressiveness, survival outcomes, and treatment response in malignancies such as breast cancer, lung cancer, gliomas, and hepatocellular carcinoma [14], [15].

The incorporation of artificial intelligence into imaging biomarker analysis also represents a major technological advancement identified throughout the review. Machine learning and deep learning algorithms have shown increasing diagnostic accuracy in lesion detection, pattern recognition, segmentation, and predictive modeling [17]. These technologies may reduce interobserver variability while improving efficiency in radiological workflows. Nevertheless, the discussion of artificial intelligence integration must also acknowledge important methodological and ethical challenges.

One of the principal concerns associated with artificial intelligence-assisted imaging involves algorithm reproducibility and generalizability. Many machine learning models are trained using institution-specific datasets that may not adequately represent diverse patient populations or imaging protocols [18]. Consequently, external validation remains essential before widespread clinical implementation can be considered reliable. Additionally, differences in scanner calibration, image acquisition parameters, and reconstruction techniques continue to affect quantitative imaging consistency.

The issue of standardization emerged as one of the most important limitations identified in the present review. Although imaging biomarkers possess considerable clinical potential, lack of harmonized protocols remains a major obstacle affecting reproducibility and multicenter validation [7], [13]. Variability in segmentation methods, computational analysis pipelines, radiomic feature extraction, and image preprocessing may significantly influence quantitative results. This limitation has motivated the development of international initiatives such as the Image Biomarker Standardization Initiative (IBSI), which aims to improve methodological consistency in radiomics research.

Another important aspect highlighted in the review involves the applicability of imaging biomarkers beyond oncology. The results demonstrated substantial utility in neurological, cardiovascular, inflammatory, hepatic, pulmonary, and metabolic diseases. In neurology, advanced MRI techniques and molecular imaging biomarkers have improved diagnostic capabilities for neurodegenerative disorders, cerebrovascular disease, epilepsy, and neuroinflammatory conditions [20]. Similarly, cardiovascular imaging biomarkers have enhanced the evaluation of myocardial fibrosis, ischemic injury, and inflammatory cardiac disease through cardiac MRI and perfusion imaging [18].

The growing relevance of imaging biomarkers in chronic inflammatory and autoimmune diseases is also noteworthy. Functional imaging techniques allow earlier detection of inflammatory activity before irreversible organ damage

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occurs, improving opportunities for timely therapeutic intervention [16]. In diseases such as systemic lupus erythematosus, vasculitis, sarcoidosis, and inflammatory bowel disease, imaging biomarkers may contribute to more accurate disease monitoring while reducing dependence on invasive diagnostic procedures.

The reviewed evidence also demonstrated the importance of elastography and fibrosis-related imaging biomarkers in chronic hepatic disease. Non-invasive quantification of liver stiffness has reduced the need for biopsy procedures while improving longitudinal monitoring of fibrosis progression [19]. Similar principles are increasingly being applied to pulmonary fibrosis, myocardial fibrosis, and systemic connective tissue disorders.

Despite these advances, the discussion must recognize that accessibility remains one of the most significant barriers affecting imaging biomarker implementation globally. The findings related to Latin America, particularly Mexico, Colombia, and Ecuador, demonstrated persistent disparities in infrastructure, technological availability, computational resources, and specialized training [17], [19]. Advanced imaging technologies such as PET/MRI, high-field MRI systems, and radiomics platforms remain concentrated primarily within tertiary-care urban centers and specialized academic institutions.

Economic limitations also continue to influence implementation capacity. Molecular imaging systems require substantial investment not only for equipment acquisition but also for maintenance, radiopharmaceutical production, computational infrastructure, and multidisciplinary personnel training. Consequently, healthcare systems with limited financial resources may experience difficulties incorporating precision imaging technologies into routine clinical practice.

The educational implications identified in this review are equally important. The evolution of imaging biomarkers has created the need for broader academic integration of quantitative radiology, computational imaging, artificial intelligence, and molecular imaging principles into undergraduate and postgraduate medical education [23]. Future physicians, radiologists, oncologists, and internists must increasingly understand the biological foundations and clinical interpretation of quantitative imaging data.

Furthermore, multidisciplinary collaboration appears essential for the future development of imaging biomarkers. Effective implementation requires integration among radiologists, oncologists, pathologists, biomedical engineers, physicists, computational scientists, and healthcare policymakers. The complexity of quantitative imaging analysis and artificial intelligence-assisted interpretation exceeds the traditional boundaries of isolated medical specialties.

The present review also highlights several future perspectives. The continued development of hybrid imaging systems, molecular tracers, radiomics platforms, and deep learning algorithms will likely expand the diagnostic and prognostic capabilities of imaging biomarkers. Personalized medicine strategies may increasingly rely on imaging-derived biological signatures capable of predicting therapeutic response and disease progression with greater precision.

Additionally, imaging biomarkers may contribute to reducing unnecessary invasive procedures by providing non-invasive surrogate markers of disease behavior. This capability possesses important implications not only for patient safety but also for healthcare efficiency and resource optimization.

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However, caution remains necessary regarding excessive technological dependence. Although quantitative imaging analysis provides valuable clinical information, imaging biomarkers should complement rather than replace comprehensive clinical evaluation. Diagnostic interpretation must continue integrating radiological findings with clinical history, laboratory studies, pathological data, and multidisciplinary judgment.

Another limitation of the current literature involves heterogeneity in study design and methodological quality. Several reviewed studies utilized retrospective designs, relatively small cohorts, or institution-specific computational models, which may limit generalizability. Prospective multicenter investigations with standardized imaging protocols will be necessary to strengthen evidence quality and facilitate broader clinical translation.

The present review itself possesses limitations that should be acknowledged. Because the study was designed as a narrative documentary review, selection bias associated with literature inclusion cannot be completely excluded. Additionally, the rapid evolution of artificial intelligence and radiomics research may lead to the emergence of new evidence after completion of the review process. Nevertheless, the incorporation of contemporary peer-reviewed scientific literature and internationally recognized sources contributes to the academic consistency of the analysis.

CONCLUSION

Imaging biomarkers have emerged as fundamental components of modern radiology and precision medicine due to their ability to provide quantitative, functional, and biologically meaningful information capable of improving clinical decision-making in systemic diseases. The evidence analyzed throughout this review demonstrates that advanced imaging techniques—including magnetic resonance imaging, computed tomography, positron emission tomography, radiomics, hybrid imaging systems, and artificial intelligence-assisted analysis—have substantially expanded the diagnostic and prognostic capabilities of contemporary medical imaging.

One of the principal conclusions of this study is that imaging biomarkers contribute significantly to early disease detection, particularly in oncology and chronic systemic disorders. Functional and molecular imaging modalities allow clinicians to identify pathological alterations before advanced structural changes become clinically evident, facilitating earlier intervention and potentially improving patient outcomes. This capability is especially relevant in malignant disease, where therapeutic success is closely associated with diagnostic timing and accurate characterization of tumor biology.

The review also demonstrates that imaging biomarkers have transformed radiology from a predominantly descriptive discipline into a quantitative and computational specialty integrated within multidisciplinary healthcare systems. Quantitative imaging analysis now allows evaluation of metabolism, cellular density, tissue perfusion, angiogenesis, inflammation, fibrosis, and tumor heterogeneity through non-invasive approaches. These advances have strengthened the role of radiology in precision medicine by supporting individualized therapeutic planning and longitudinal disease monitoring.

Radiomics and artificial intelligence represent some of the most promising developments identified in the analyzed literature. High-throughput computational image analysis enables extraction of complex imaging features associated with molecular behavior, treatment response, and prognostic outcomes that may not be visually perceptible through conventional interpretation alone. Similarly, machine learning algorithms possess increasing potential to improve diagnostic efficiency, reduce interpretation variability, and optimize radiological workflows. Nevertheless, important

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challenges related to validation, reproducibility, ethical considerations, and external generalizability remain unresolved.

Another important conclusion involves the broad applicability of imaging biomarkers beyond oncology. Neurological, cardiovascular, inflammatory, hepatic, pulmonary, and metabolic diseases all demonstrated substantial benefit from quantitative imaging approaches. Advanced imaging biomarkers contribute not only to disease detection but also to severity assessment, prognostic estimation, therapeutic monitoring, and evaluation of systemic organ involvement. Consequently, imaging biomarkers are progressively becoming essential tools within internal medicine and chronic disease management.

Despite these advances, the review identified significant limitations affecting the widespread implementation of imaging biomarkers, particularly in developing healthcare systems. Infrastructure limitations, high technological costs, insufficient access to hybrid imaging systems, training gaps, lack of standardization, and restricted artificial intelligence integration continue to affect healthcare accessibility in Latin America, including Mexico, Colombia, and Ecuador. These disparities emphasize the importance of international collaboration, educational modernization, technological investment, and standardized imaging protocols.

The educational implications of imaging biomarker integration are also highly relevant. Contemporary medical education must increasingly incorporate quantitative imaging principles, radiomics methodologies, molecular imaging concepts, and computational radiology into undergraduate and postgraduate curricula. Future healthcare professionals will require multidisciplinary competencies capable of integrating radiological, biological, technological, and clinical information within precision medicine environments.

Additionally, the review highlights the importance of maintaining a balanced perspective regarding technological innovation. Although imaging biomarkers provide valuable quantitative information, they should complement rather than replace comprehensive clinical evaluation and multidisciplinary medical judgment. Clinical interpretation must continue integrating imaging findings with patient history, laboratory data, pathological analysis, and individualized healthcare considerations.

Future perspectives suggest that imaging biomarkers will continue evolving alongside advances in molecular imaging, computational medicine, hybrid imaging systems, and artificial intelligence technologies. Continued research focused on standardization, multicenter validation, reproducibility, and healthcare accessibility will be essential to strengthen clinical implementation and optimize patient-centered care.

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