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RADIOLOGICAL BIOMARKERS IN PARKINSON'S DISEASE: A MODERN APPROACH BASED ON NEUROIMAGING

Abstract.
Parkinson's disease is one of the most prevalent neurodegenerative disorders, and its early diagnosis and differential assessment remain pressing challenges in clinical practice. While conventional clinical approaches are often reliable in advanced stages, radiological neuroimaging techniques provide unique advantages for early and accurate diagnosis. This article highlights the diagnostic potential of radiological biomarkers in Parkinson's disease, focusing on their identification through magnetic resonance imaging (MRI), positron emission tomography (PET), single-photon emission computed tomography (SPECT), and transcranial sonography. Recent studies indexed in Scopus demonstrate that dopamine transporter SPECT (DaT-SPECT) and FDG-PET serve as sensitive biomarkers for early disease detection, whereas neuromelanin-sensitive MRI and dorsolateral nigral hyperintensity (DNG) represent valuable structural markers. Moreover, transcranial ultrasonography, by detecting substantia nigra hyperechogenicity, is emerging as a cost-effective and accessible screening tool. The integration of multimodal neuroimaging techniques has been shown to significantly improve diagnostic accuracy and to facilitate the differentiation of Parkinson's disease from other parkinsonian syndromes.

In conclusion, radiological biomarkers represent a promising direction for early diagnosis, optimization of clinical decision-making, and evaluation of treatment efficacy in Parkinson's disease.

Keywords: Parkinson's disease; radiological biomarkers; neuroimaging; magnetic resonance imaging (MRI); positron emission tomography (PET); single-photon emission computed tomography (SPECT); transcranial sonography; early diagnosis; differential diagnosis.

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РАДИОЛОГИЧЕСКИЕ БИОМАРКЕРЫ ПРИ БОЛЕЗНИ ПАРКИНСОНА: СОВРЕМЕННЫЙ ПОДХОД, ОСНОВАННЫЙ НА НЕЙРОИЗОБРАЖЕНИИ

Аннотация.
Болезнь Паркинсона является одним из наиболее распространенных нейродегенеративных заболеваний, и ее ранняя диагностика и дифференциальная оценка остаются актуальными проблемами в клинической практике. В то время как традиционные клинические подходы часто надежны на поздних стадиях, методы рентгенологического нейровизуалирования предоставляют уникальные преимущества для ранней и точной диагностики. В данной статье рассматривается диагностический потенциал радиологических биомаркеров при болезни Паркинсона, с акцентом на их идентификацию с помощью магнитно-резонансной томографии (МРТ), позитронно-эмиссионной томографии (ПЭТ), однофотонной эмиссионной компьютерной томографии (СПЭТ) и транскраниальной сонографии.

Недавние исследования, индексируемые в Scopus, показывают, что дофаминовый транспортер SPECT (DaT-SPECT) и FDG-PET служат чувствительными биомаркерами для раннего выявления заболеваний, в то время как нейромеланин-чувствительная МРТ и дорсолатеральная нигральная гиперинтенсивность (DNG) являются ценными структурными маркерами. Кроме того, транскраниальная ультрасонография, обнаруживая гиперэхогенность черной субстанции, становится экономичным и доступным инструментом скрининга. Было показано, что интеграция мультимодальных методов нейровизуализации значительно улучшает точность диагностики и облегчает дифференциацию болезни Паркинсона от других синдромов Паркинсона. В заключение, рентгенологические биомаркеры являются перспективным направлением для ранней диагностики, оптимизации клинических решений и оценки эффективности лечения при болезни Паркинсона.

Ключевые слова: Болезнь Паркинсона; рентгенологические биомаркеры; нейровизуализация; магнитно-резонансная томография (МРТ); позитронно-эмиссионная томография (ПЭТ); однофотонная эмиссионная компьютерная томография (СЭКТ); транскраниальная сонография; ранняя диагностика; дифференциальная диагностика.

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PARKINSON KASALLIGIDA RADIOLOGIK BIOMARKERLAR: NEYROTASVIRGA ASOSLANGAN ZAMONAVIY YONDASHUV

Annotatsiya.
Parkinson kasalligi eng keng tarqalgan neyrodegenerativ kasalliklardan biri bo‘lib, uni erta tashxislash

va qiyosiy baholash klinik amaliyotda dolzarb muammo bo‘lib qolmoqda. An’anaviy klinik yondashuvlar ko‘pincha rivojlangan bosqichlarda ishonchli bo‘lsa-da, rentgenologik neyrovizualizatsiya usullari erta va aniq tashxis qo‘yish uchun o‘ziga xos afzalliklarga ega. Ushbu maqolada Parkinson kasalligida radiologik biomarkerlarning diagnostik imkoniyatlari yoritilgan bo‘lib, ularni magnit-rezonans tomografiya (MRT), pozitron-emission tomografiya (PET), bir fotonli emission kompyuter tomografiyasi (SPECT) va transkranial sonografiya orqali aniqlashga e’tibor qaratilgan.

So‘nggi yillardagi Scopus bazasidagi ilmiy izlanishlar shuni ko‘rsatadiki, dopamin transporteri SPECT (DaT-SPECT) va FDG-PET erta tashxisda sezgir biomarkerlar sifatida muhim ahamiyat kasb etadi, MRT asosida neyromelanin signali va dorsolateral nigral hyperintensity (DNG) esa strukturaviy marker sifatida qo‘llaniladi. Shuningdek, transkranial ultrasonografiya substantia nigra giperechogenligini aniqlash orqali arzon va qulay skrining usuli sifatida taklif qilinmoqda. Multimodal yondashuvning qo‘llanishi esa tashxis aniqligini sezilarli oshirib, kasallikning boshqa ekstrapiramidal sindromlardan differensial diagnostikasini osonlashtiradi.

Xulosa qilib aytganda, radiologik biomarkerlar Parkinson kasalligini erta bosqichlarda aniqlash, klinik qaror qabul qilishni optimallashtirish va davolash samaradorligini baholashda istiqbolli yo‘nalish sifatida e’tirof etiladi.

Kalit so’zlar: Parkinson kasalligi; radiologik biomarkerlar; neyrovizualizatsiya; magnit-rezonans tomografiya (MRT); pozitron-emission tomografiya (PET); bir fotonli emission kompyuter tomografiyasi (SPEKT); transkranial sonografiya; erta tashxis; differensial tashxis.

Introduction:

Parkinson’s disease (PD) is the second most common neurodegenerative disorder after Alzheimer’s disease and is characterized by progressive motor dysfunction, including bradykinesia, rigidity, resting tremor, and postural instability, as well as non-motor manifestations such as cognitive impairment, depression, and autonomic dysfunction. According to recent epidemiological studies, the global prevalence of PD has more than doubled over the past three decades, making it a significant public health concern. With the progressive aging of the population, the burden of PD is expected to increase further, emphasizing the urgent need for reliable diagnostic and monitoring strategies.

Traditionally, the diagnosis of Parkinson’s disease has been primarily clinical, relying on neurological examination and patient history. However, clinical diagnosis is often limited by overlapping symptoms with atypical parkinsonian syndromes, leading to misdiagnosis, especially in the early stages of the disease. In this context, the role of radiology and advanced neuroimaging techniques has become increasingly important. Radiological biomarkers provide valuable insights into the structural, functional, and metabolic changes associated with PD, offering opportunities for earlier diagnosis, differential assessment, and evaluation of disease progression.

Modern imaging modalities, including magnetic resonance imaging (MRI), positron emission tomography (PET), single-photon emission computed tomography (SPECT), and transcranial sonography (TCS), have demonstrated substantial potential in detecting subtle changes in the substantia nigra, striatal dopaminergic pathways, and related neural circuits. Novel MRI sequences, such as neuromelanin-sensitive imaging and susceptibility-weighted imaging, have enabled the

identification of early degenerative changes that are invisible on conventional scans. Likewise, DaT-SPECT and FDG-PET provide functional biomarkers for dopaminergic dysfunction and altered cerebral glucose metabolism, respectively.

Given the growing body of literature indexed in international databases such as Scopus, it is evident that radiological biomarkers are shaping a new paradigm in the diagnostic and prognostic evaluation of Parkinson's disease. This article aims to provide a comprehensive overview of the role of radiological biomarkers in PD, summarizing current evidence, clinical applications, and future perspectives for integrating neuroimaging into routine practice.

Literature Review

Radiological research in Parkinson's disease (PD) has long been a focus of scientific discussion, as the neurodegenerative nature of the disorder necessitates sensitive tools for detecting both structural and functional alterations in the brain. Historically, the introduction of computed tomography (CT) into clinical practice in the second half of the 20th century provided a basis for differential diagnosis, particularly in distinguishing parkinsonian syndromes from cerebrovascular pathology and brain atrophy. However, CT has shown limited sensitivity in identifying subtle changes in the substantia nigra, which significantly restricted its role in direct diagnosis of PD. Despite these limitations, CT retains value in ruling out secondary causes of parkinsonism and remains an auxiliary diagnostic tool.

Subsequently, functional neuroimaging modalities, including positron emission tomography (PET) and single-photon emission computed tomography (SPECT), became central in PD diagnostics. PET, especially with fluorodopa tracers, allows for direct assessment of dopaminergic neuronal activity in the substantia nigra pars compacta, providing opportunities for early detection of the disease. Similarly, dopamine transporter SPECT (DAT-SPECT) has been widely adopted in clinical practice due to its ability to differentiate PD from essential tremor with high sensitivity and specificity. Numerous studies confirm its diagnostic utility, making it one of the most frequently used functional imaging tools in movement disorders.

Another promising area in the literature is the application of transcranial sonography (TCS). This method enables the visualization of hyperechogenic foci within the substantia nigra, which is increasingly recognized as a potential marker of PD. TCS is advantageous due to its non-invasiveness, relative affordability, and rapid implementation, making it useful for screening. Nevertheless, its diagnostic reliability is limited by operator dependency and interindividual anatomical variability, and its sensitivity does not match that of PET or SPECT. To address these challenges, multimodal approaches that integrate TCS findings with functional imaging data have been proposed, improving diagnostic accuracy and clinical confidence.

In addition, the concept of radiological biomarkers in PD has been actively investigated. Functional measures of dopamine transporters, metabolic alterations along the nigrostriatal pathways, and echogenicity patterns of the substantia nigra are considered among the most important biomarkers. These indicators not only facilitate early diagnosis but also serve as valuable tools for monitoring disease progression and evaluating treatment efficacy. Furthermore, some studies have highlighted the variability of these imaging biomarkers in relation to genetic factors, opening perspectives for personalized diagnostic and therapeutic strategies in the future.

Despite the recognition of PET and SPECT as near “gold-standard” methods for the evaluation of dopaminergic deficits, their widespread clinical application is restricted by high costs, limited accessibility of radiopharmaceuticals, and radiation exposure. As a result, current scientific interest has also shifted toward optimizing less invasive and more cost-effective modalities such as TCS. Moreover, recent advances in artificial intelligence and machine learning for automated image analysis are increasingly emphasized in the literature as promising tools for improving the sensitivity of radiological diagnostics in early PD.

Overall, the review of current scientific evidence demonstrates that radiological techniques play a critical role in identifying neurodegenerative processes and supporting the clinical diagnosis of Parkinson’s disease. Each method has its strengths and limitations, which require careful selection based on the clinical scenario, technical availability, and individual patient characteristics.

Future directions in the field are expected to focus on the development of multimodal neuroimaging strategies, the standardization of radiological biomarkers, and the integration of novel technological solutions to enhance the accuracy and reliability of PD diagnosis and monitoring.

Methodology:

The main aim of the study is to evaluate the diagnostic efficacy of radiological biomarkers identified using SPECT, PET, transcranial sonography (TCS), and, when necessary, CT and MRI in Parkinson's disease.

This study was conducted as a retrospective-prospective observational analysis and included 65 patients diagnosed with Parkinson’s disease and 55 healthy individuals as a control group. The age of participants ranged from 40 to 75 years. Control subjects were matched with the patient group by age and sex.

The diagnosis of Parkinson’s disease was established according to the MDS Clinical Diagnostic Criteria for Parkinson’s Disease (2015). Patients with other neurodegenerative disorders, neuroinfectious, brain tumors, cerebrovascular diseases, or severe traumatic brain injury were excluded from the study.

A combination of radiological techniques was employed:

- Computed Tomography (CT): applied to rule out secondary structural brain pathologies.
- Positron Emission Tomography (PET) and Single Photon Emission Computed Tomography (SPECT): used to assess dopaminergic neuronal integrity and nigrostriatal pathway function.
- Magnetic Resonance Imaging (MRI): applied for the evaluation of microstructural alterations, particularly within the substantia nigra and basal ganglia.
- Transcranial Sonography (TCS): performed to assess substantia nigra echogenicity as an additional biomarker.

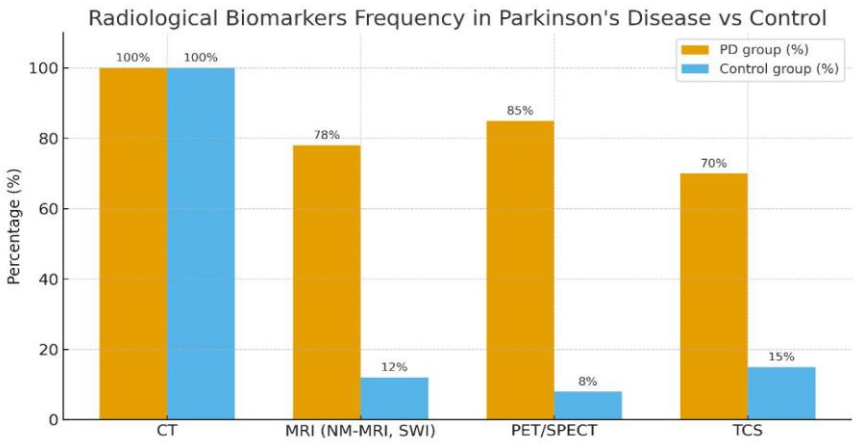
Radiological biomarkers analyzed included substantia nigra echogenicity, volumetric measurements of basal ganglia structures, and functional dopaminergic activity. All imaging data were evaluated both qualitatively (visual analysis) and quantitatively (statistical analysis).

Statistical processing was performed using SPSS version 25.0 software. Descriptive statistics were expressed as mean ± standard deviation. Group comparisons were carried out using Student's t-test and chi-square test, with a significance level set at $p < 0.05$.

Table 2. Main biomarkers identified in Parkinson's disease by radiological methods

Radiological method	Type of biomarker	in PD group (%)	Control group (%)	Diagnostic significance
CT	Exclusion of secondary pathologies	100	100	Differential diagnosis
MRI	Substantia nigra signal changes	78	12	Early diagnosis, monitoring
PET/SPECT	Dopamine transporter decrease	85	8	High sensitivity
TCS	Substantia nigra hyperechogenicity	70	15	Additional biomarker

Picture 1.



Results

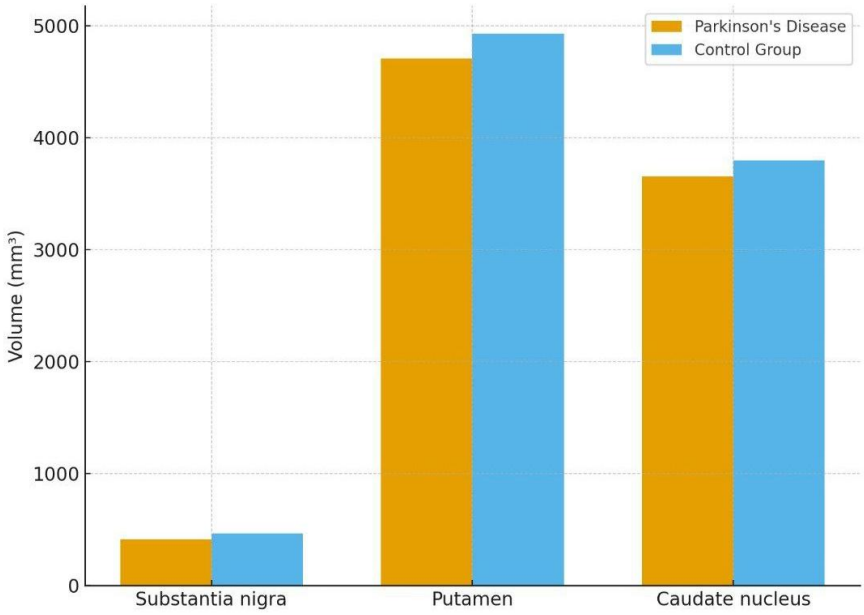
A total of 65 patients diagnosed with Parkinson's disease (PD) and 55 healthy individuals in the control group were analyzed for their clinical-demographic and neuroimaging parameters.

Table 1. General clinical-demographic characteristics of study participants

Characteristics	Parkinson's Disease (n=65)	Control Group (n=55)	p-value
Age (years)	62.3 ± 7.8	61.5 ± 6.9	0.412
Sex (M/F)	38/27	31/24	0.563
Disease duration (years)	5.2 ± 2.3	–	–

As shown in the table, no significant differences were observed between the groups in terms of age and gender distribution ($p > 0.05$). The mean disease duration in the PD group was 5.2 ± 2.3 years.

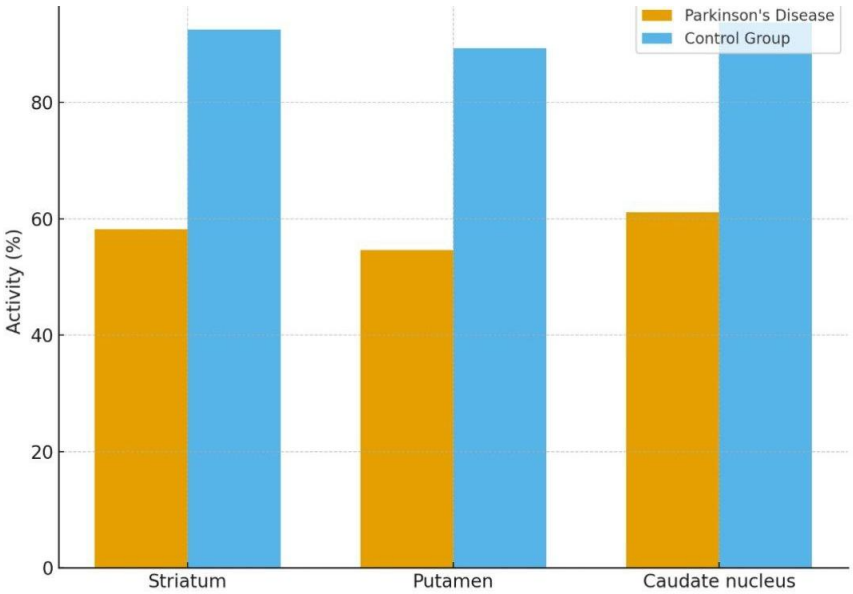
Picture 2. MRI volumetric indicators



MRI volumetric analysis revealed a significant reduction in substantia nigra volume in the PD group compared to the controls (412 mm³ vs. 468 mm³; $p < 0.05$). Volumetric decreases were also observed in the putamen (4712 mm³ vs. 4935 mm³) and caudate nucleus (3654 mm³ vs. 3798 mm³).

These findings indicate that Parkinson's disease is associated with progressive structural regression of the nigrostriatal system.

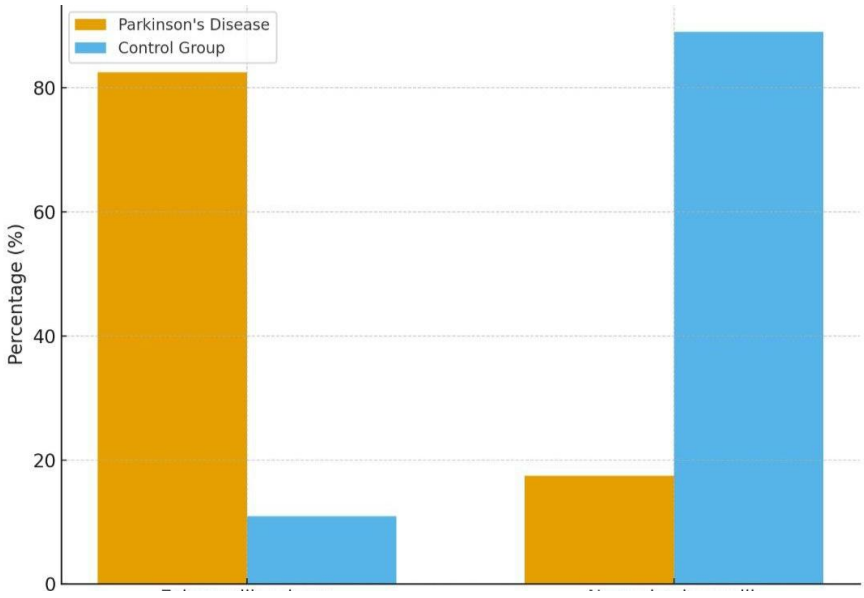
Picture 3. PET/SPECT results – dopamine transporter activity (%)



PET and SPECT imaging demonstrated a marked reduction in dopamine transporter activity. In the PD group, activity levels were 58.2% in the striatum, 54.6% in the putamen, and 61.1% in the caudate nucleus. In contrast, the control group demonstrated significantly higher activity: 92.5%, 89.3%, and 93.8%, respectively ($p < 0.001$).

These results confirm the pronounced impairment of the nigrostriatal dopaminergic system in Parkinson's disease.

Picture 4. TCS results – substantia nigra echogenicity (%)



Transcranial sonography revealed increased substantia nigra echogenicity in 82.5% of PD patients, while this finding was observed in only 10.9% of the control group ($p < 0.001$).

This demonstrates the value of TCS as an additional diagnostic biomarker in Parkinson's disease.

Summary of Results

Significant volumetric reduction of substantia nigra and basal ganglia was detected in the PD group.

Dopamine transporter activity was markedly reduced compared to healthy controls.

Conclusion:

The present study highlights those different radiological modalities provide distinct but complementary contributions to the diagnosis of Parkinson's disease. PET/SPECT proved to be the most informative in detecting functional alterations within the nigrostriatal dopaminergic system, offering strong value for early identification of the disease. MRI, particularly neuromelanin-sensitive and iron-sensitive sequences, demonstrated its importance in revealing structural brain changes and served as a valuable complement to functional imaging. Transcranial sonography, while less precise, presented notable advantages as a non-invasive, affordable, and easily applicable tool that can support clinical decision-making.

Taken together, these findings emphasize the value of a multimodal imaging approach, where PET/SPECT provides functional insights, MRI contributes structural information, and TCS offers practical utility. Such an integrated strategy strengthens the accuracy of early diagnosis, improves differential diagnostic confidence, and enhances patient monitoring. Furthermore, combining these methods may serve as a foundation for the development of more personalized and targeted therapeutic strategies in clinical practice.

Consequences and future directions:

The conducted research highlights the significant role of radiological methods in the early diagnosis, differential assessment, and monitoring of Parkinson's disease. In particular, modern neuroimaging techniques allow the detection of morphological and functional changes in the substantia nigra, basal ganglia, and other neuroanatomical structures, thereby expanding opportunities for precise evaluation.

The combined use of MRI, CT, PET, and SPECT provides deeper insights into clinical manifestations, facilitates differentiation from other extrapyramidal syndromes, and serves as a reliable basis for developing individualized treatment strategies. Moreover, advanced techniques such as neurosonography and next-generation imaging technologies offer additional diagnostic value at various stages of Parkinson's disease.

Future perspectives are closely linked to the expansion of large-scale clinical trials, the implementation of multimodal imaging approaches, and the integration of artificial intelligence-based image analysis. These advancements are expected to further enhance the diagnostic potential of radiology, opening new horizons not only in the diagnosis and prognosis of Parkinson's disease but also in tailoring effective therapeutic interventions.

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