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Digital Platform for the Prediction of 3D Visual and 3D Ultrastructural Morphology of the Urinary Tract

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Abstract

Background: Inflammatory diseases of the urinary system remain a significant clinical challenge in urology, and current diagnostic methods are limited in their ability to assess morphological and functional changes at the molecular and ultrastructural levels. The development of comprehensive digital tools integrating functional imaging with ultrastructural analysis is necessary to improve diagnosis and monitoring.

Methods and Results: This pilot study included 8 patients divided into two groups: inflammatory kidney diseases (n=4) and bladder inflammation (n=4). Data from PET/CT scans using ^{18}F-FDG and ^{11}C-choline were integrated with 3D anatomical reconstruction and 3D ultrastructural analysis performed by scanning and transmission electron microscopy. A clear relationship was established between the SUVmax of radiopharmaceuticals and the 3D anatomical and 3D ultrastructural changes reflecting bacterial inflammation activity. Clinical navigation schemes were developed enabling physicians to retrospectively assess the probable 3D visual and ultrastructural state of the urinary system using digital PET/CT indicators.(**International Journal of Biomedicine. 2026;16(3):378-382.**)

Keywords: digital imaging • PET/CT • scanning electron microscopy • urinary tract inflammation

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Introduction

Inflammatory diseases of the urinary system remain among the most prevalent and clinically significant challenges in urology.[1–3] Despite a broad spectrum of available diagnostic modalities—including laboratory testing, ultrasonography, computed tomography (CT), and magnetic resonance imaging (MRI)—accurate quantitative and qualitative assessment of morphological and functional changes at the molecular and ultrastructural levels remains a considerable challenge for the practicing clinician.[4] The limited resolution of conventional imaging technologies and the lack of an integrated analytical approach diminish the effectiveness of early detection of pathological alterations and longitudinal monitoring of inflammatory disease activity.[5] Over the past decades, the advent of whole-body positron emission tomography/computed tomography (PET/CT) has opened new avenues for evaluating the metabolic activity of inflammatory processes in the kidneys and urinary bladder.[6,7] However, in routine clinical practice, the functional information provided by PET/CT is predominantly used to detect neoplastic pathologies, whereas the interpretation of inflammation-related changes in scanned organs remains insufficiently developed.[8–11] Contemporary three-dimensional (3D) reconstruction techniques, based on high-precision data from advanced and resource-intensive research modalities, enable the acquisition of detailed ultrastructural images of pathological alterations. This capability is critically important for a deeper understanding of the pathogenesis of inflammatory processes and for the accurate assessment of their activity.[12–15] In this context, multidisciplinary approaches that combine functional and ultrastructural 3D visualization are of considerable interest. One such approach is the integration of PET/CT diagnostic data with findings from ultrastructural and clinical investigations. [16-17] Given the growing demand for personalized medicine and precision diagnostics in inflammatory diseases, there is a pressing need to develop digital analytical platforms. Such platforms would enable clinicians—without requiring in-depth expertise in nuclear medicine, 3D technologies, or electron microscopy—to rapidly and reliably assess the 3D visual and 3D ultrastructural state of the kidneys and urinary bladder based on standardized uptake values (SUV) of radiopharmaceuticals.

Therefore, the development and implementation of a digital analytical platform will not only improve the accuracy of diagnosis and monitoring of inflammatory processes but also lay the groundwork for the creation of novel clinical navigation algorithms, ultimately enhancing treatment efficacy and patient quality of life.

Objective

This study aimed to develop a digital analytical platform capable of retrospectively assessing, based on whole-body PET/CT digital data, the probable 3D visual and 3D ultrastructural state of urinary system organs in patients with inflammatory diseases of the kidneys and urinary bladder.

Materials and Methods

Study Design and Patient Population

This pilot study was based on the results of a comprehensive examination of eight patients treated at the Urology Department of the Tyumen Regional Clinical Hospital No. 2 between 2020 and 2023. The study was conducted in accordance with the Declaration of Helsinki and approved by the institutional ethics committee. All participants provided written informed consent.

Group 1 comprised three women and one man, with a median age of 39.5 years (range: 28–42), who had undergone nephrectomy for the following indications: acute purulent pyelonephritis with multiple parenchymal carbuncles (n=1), chronic pyelonephritis resulting in malignant nephrogenic hypertension with a preserved contralateral kidney (n=1), and a non-functioning, secondarily shrunken pyelonephritic kidney (n=2). The inclusion criteria were as follows: a history of nephrectomy for one of the specified diagnoses, whole-body ^{18}F-FDG PET/CT performed before surgery, age over 18 years, and provision of informed consent. Exclusion criteria included: an unverified diagnosis underlying the nephrectomy, the presence of renal or urinary tract malignancy, and severe decompensated comorbidities.

In the first case, ^{18}F-FDG PET/CT was performed to investigate a potential oncological cause of fever of unknown origin; in the remaining three cases, the scan was undertaken to exclude oncological causes of persistent isolated urinary syndrome with microhematuria. For comparative analysis, we used whole-body ^{18}F-FDG PET/CT images from Patient I., a 42-year-old male with no nephrourological history, and ultrastructural examination data of a kidney specimen from Patient A., a 38-year-old male without nephrourological history, whose kidney was removed due to traumatic avulsion from the renal pedicle.

For each case in the study group, 3D anatomical reconstruction of the sectional renal anatomy was generated from the post-nephrectomy gross specimen using our proprietary computer software. Concurrently, 3D ultrastructural reconstruction of all nephron elements within a single integrated block was performed based on transmission electron microscopy (TEM) at ×10,000 magnification.

Group 2 consisted of three women and one man, with a median age of 41.5 years (range: 30–45), who presented with inflammatory diseases of the urinary bladder. All had previously undergone ^{11}C-choline PET/CT to rule out oncological causes of persistent isolated urinary syndrome with microhematuria. During hospitalization, all patients underwent cystoscopy with targeted biopsy under general anesthesia. For comparative analysis, we used whole-body ^{11}C-choline PET/CT images from Patient M., a 42-year-old female with no nephrourological history, and ultrastructural findings from the bladder wall of Patient Sh., a 29-year-old male without nephrourological history, whose tissue was obtained during surgical debridement and closure of a traumatic bladder rupture.

For each case in Group 2, 3D visual reconstruction of the bladder mucosa was generated from the cystoscopic findings using our proprietary computer software. Additionally, 3D ultrastructural reconstruction of all bladder wall elements within a single integrated block was performed based on scanning electron microscopy (SEM) at ×6,000 magnification.

PET/CT Imaging

Whole-body PET/CT was performed according to a standard protocol using a Biograph PET/CT scanner (Siemens, Germany) installed at the Radiology Center of the Tyumen Regional Oncology Center. Functional changes in the renal parenchyma and bladder wall were evaluated based on tissue affinity for the radiopharmaceuticals. Regions of interest were analyzed automatically for standardized uptake values (SUV) in minimal (SUVmin), average (SUVavg), and maximal (SUVmax) ranges within comparable tissue volumes (cm^3). Radiopharmaceuticals were synthesized on-site using a compact cyclotron (Scanditronix, Sweden).

Electron Microscopy

Scanning electron microscopy (SEM) was performed at the Tyumen Scientific Center, Siberian Branch of the Russian Academy of Sciences, using a Hitachi High-Tech SU3800/SU3900 scanning electron microscope (Japan). Transmission electron microscopy (TEM) was employed for ultrastructural analysis of nephron elements at ×10,000 magnification, while SEM was utilized for 3D ultrastructural reconstruction of bladder wall elements at ×6,000 magnification.

Integrated Data Analysis

Based on the results of high-technology and research-intensive investigations, we assessed the relationship between the maximal standardized uptake value (SUVmax), obtained non-invasively by PET/CT, and the characteristic 3D visual and 3D ultrastructural tissue manifestations of pathology, obtained invasively by scanning and transmission electron microscopy.

Results

The comprehensive investigations conducted in this pilot study established a clear relationship among patients with renal pathology between the standardized uptake value of ^{18}F-FDG (SUVmax) in the renal parenchyma, the corresponding 3D anatomical features of sectional kidney anatomy, and the 3D ultrastructural state of all nephron elements within a single integrated block, reflecting varying degrees of bacterial inflammatory activity.

The assessment of the 3D ultrastructural state of the nephron was based on the visual analysis of the following parameters: podocyte size, organelle density within the podocyte, the condition of the basement membrane, the

presence of pathological contents within the urinary space, and the structural integrity of the proximal and distal tubules (Figure 1).

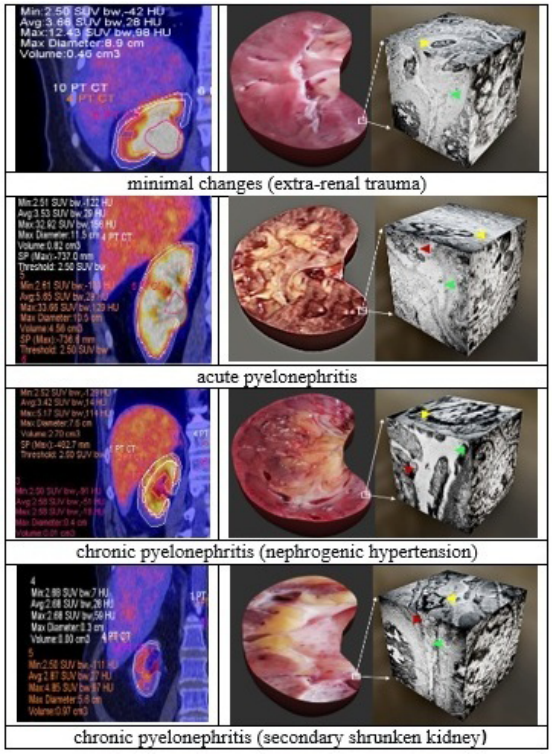

Figure 1. *Correlation of SUVmax values with the anatomical 3D reconstruction of the renal parenchyma and the segmented ultrastructural 3D reconstruction of the nephron.*

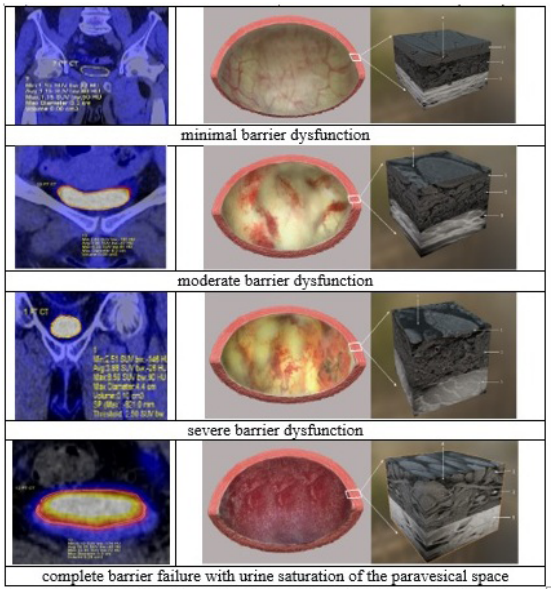

Figure 2. *Correlation of SUVmax values with the 3D cystoscopic view and the 3D ultrastructural condition of the bladder wall within a single integrated block.*

In Group 2, we analyzed a possible relationship between the SUVmax of ^{11}C-choline uptake in the bladder wall, the 3D cystoscopic appearance, and the 3D ultrastructural manifestations of impaired bladder barrier function, which leads to the saturation of the bladder wall layers with urine containing ^{11}C-choline. By assessing visual changes in cell size, the structural organization of superficial urothelial cells, and the presence and width of intercellular spaces, we evaluated the likelihood of urine penetration—containing not only ^{11}C-choline but also toxic peroxide enzymes and oxygen free radicals—into the deeper layers of the bladder wall (Figure 2).

Based on the relationships identified from multilevel imaging, we developed a clinical navigation scheme for practicing urologists. Using this scheme, a urologist—without specialized expertise in nuclear medicine or 3D ultrastructural analysis—can retrospectively determine, by referencing the affinity of the renal parenchyma for ^{18}F-FDG (SUVmax), the probable 3D anatomical state of the renal parenchyma and the 3D ultrastructural changes in all nephron elements within a single integrated block characteristic of bacterial inflammation at ×10,000 magnification (Figure 3).

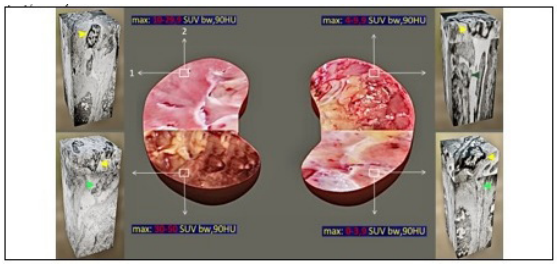

Figure 3. *Clinical navigation scheme of the probable 3D ultrastructural state of the nephron at 10,000× magnification and the 3D anatomical structure of the renal parenchyma based on the digital PET/CT standardized uptake value (SUV) of 18F-FDG.*

A similar clinical navigation scheme was developed to assess the likelihood of impaired bladder barrier function as one cause of recurrent cystitis. Using this scheme, a physician without specialized training in nuclear medicine or ultrastructural research methods can retrospectively determine, based on the digital values of bladder wall affinity for ^{11}C-choline, the probable 3D cystoscopic appearance and the 3D ultrastructural state of all bladder wall elements within a single integrated block (Figure 4).

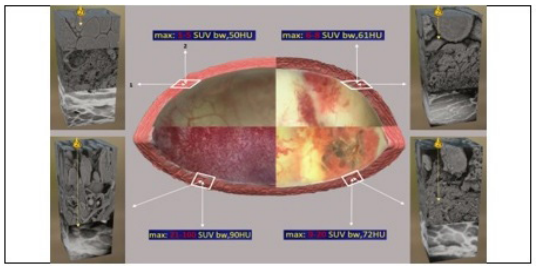

Figure 4. *Clinical navigation scheme of the probable 3D cystoscopic view of the mucosa and the 3D ultrastructural condition of the bladder wall's barrier functions at 6000× magnification, based on the digital standardized uptake value (SUV) of 11C-choline from PET/CT results.*

Discussion

This pilot study, which investigated the PET/CT-based molecular, cellular, and ultrastructural characteristics of the renal parenchyma and bladder wall elements, resulted in the development of a digital analytical platform. This platform enables the modeling of the probable 3D visual appearance and 3D ultrastructural state of the urinary system organs in the setting of inflammatory diseases, using data from ^{18}F-FDG and ^{11}C-choline PET/CT. The findings indicate a close relationship between the standardized uptake values of the radiopharmaceuticals (SUVmax) and the 3D ultrastructural manifestations of inflammation in both the renal parenchyma and the bladder wall.

Specifically, varying degrees of bacterial inflammatory activity within the renal parenchyma were associated with distinct changes in the digital SUVmax values for ^{18}F-FDG, which correlated with the severity of structural alterations in the nephron—the fundamental functional unit of the kidney. In the context of clinical and laboratory manifestations of bacterial cystitis, the digital SUVmax value for ^{11}C-choline reflected the integrity of the bladder's barrier function, specifically its capacity to prevent toxic urinary products—including enzymes, peroxides, and free radicals—from penetrating the deeper layers of the bladder wall.

These data support the feasibility and clinical relevance of integrating functional imaging with multilevel morphological analysis. The multidisciplinary approach implemented within our developed digital platform enhances the understanding of the pathogenesis of inflammatory diseases, which is essential for accurate diagnosis and monitoring and cannot be achieved by other currently available examination methods. This is particularly pertinent given the increasing demand for integrating digital technologies and artificial intelligence into routine clinical practice, ultimately contributing to improved clinical outcomes and enhanced quality of life for our patients.

Study Limitations

The present study has several limitations. This is a pilot investigation, and further research is required before widespread clinical implementation can be considered. An additional limitation is the absence of a comprehensive statistical analysis. A significant practical limitation at present is the high cost and limited availability of PET/CT imaging. Consequently, the results presented herein should be regarded as preliminary and require validation in larger studies with expanded sample sizes, a comparative design, and robust statistical analysis.

Conclusion

In this pilot study, we developed a digital analytical platform that enables the assessment of the probable 3D visual and 3D ultrastructural state of the urinary system organs in the setting of urological inflammatory diseases, based on PET/CT tissue affinity values for radiopharmaceuticals. The proposed clinical navigation schemes allow urologists to model, in an accessible and intuitive format, the probable condition of the kidneys and urinary bladder without the need for resource-intensive, high-technology investigations, thereby facilitating more accurate diagnosis and personalized treatment.

The limitations and shortcomings of our work are related to the pilot nature of the study, and larger-scale clinical investigations are required to confirm the efficacy of the proposed approach definitively.

Conflict of Interest

The authors have declared no conflict of interest.

Author Contributions

Boris A. Berdichevskiy: Conceptualization, Methodology, Supervision, Project administration, Writing – review & editing.
Grigory V. Zubik: Investigation, Data curation, Formal analysis, Software, Writing – original draft.
All authors have read and approved the final version of the manuscript.

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