IMAGING IN RENAL CELL CARCINOMA DETECTION

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Abstract. Renal cell carcinoma (RCC) is one of the most common malignancies of the urinary system, characterized by a high rate of incidental detection due to the widespread use of modern imaging techniques. Early and accurate diagnosis plays a critical role in improving patient outcomes and guiding appropriate therapeutic strategies. This thesis explores the role of contemporary imaging modalities in the detection and characterization of RCC.

The study analyzes the diagnostic value of ultrasound (US), computed tomography (CT), and magnetic resonance imaging (MRI) in identifying renal masses, differentiating benign from malignant lesions, and staging the disease. Particular attention is given to contrast-enhanced imaging techniques, which significantly improve lesion detection, vascular assessment, and tumor characterization. In addition, the potential of advanced imaging approaches, including multiparametric MRI and radiomics, is discussed in the context of personalized medicine.

Keywords: renal cell carcinoma, renal mass, kidney tumor, computed tomography, magnetic resonance imaging, ultrasound, contrast-enhanced ultrasound, multiphasic imaging, indeterminate renal mass, diagnostic radiology.

Relevance of the topic: Renal cell carcinoma (RCC) is the most common primary malignant tumor of the kidney in adults and remains one of the key oncological problems in abdominal radiology. The expansion of ultrasound, computed tomography, and magnetic resonance imaging in general clinical practice has led to a marked rise in the incidental detection of asymptomatic renal masses. This trend is clinically important because early imaging detection may reveal organ-confined tumors at a stage when nephron-sparing treatment is possible. At the same time, increased incidental discovery has created a major diagnostic challenge: not every renal mass is malignant, and not every malignant lesion has the same biological behavior. Therefore, accurate imaging is essential not only for identifying RCC, but also for differentiating it from benign entities, estimating aggressiveness, planning biopsy or surgery, and defining the need for follow-up. Contemporary guideline documents continue to consider imaging a fundamental component of RCC evaluation, while recent radiology reviews emphasize the growing role of contrast-enhanced ultrasound and advanced functional techniques as complements to CT and MRI. In this context, a structured analysis of the current imaging approach to RCC detection remains highly relevant for clinical radiology and oncological decision-making.

Aim of the study: The aim of this thesis was to analyze the diagnostic role of modern imaging methods in renal cell carcinoma detection, to compare the strengths and limitations of conventional ultrasound, contrast-enhanced computed tomography, magnetic resonance imaging, and contrast-enhanced ultrasound, and to formulate a practical multimodality approach for the radiological assessment of suspected renal malignancy.

Materials and methods: This thesis was prepared as a structured narrative review based on guideline recommendations, peer-reviewed radiology publications, and recent review articles focused on renal mass characterization and RCC detection.

The material included literature on the diagnostic evaluation of incidentally detected renal masses, imaging strategies for small renal tumors, enhancement-based differentiation of malignant and benign lesions, and the role of advanced imaging in local staging. The analysis emphasized clinically relevant imaging variables: lesion size, border definition, exophytic or endophytic growth, echogenicity on ultrasound, measurable enhancement on CT and MRI, diffusion characteristics, microvascular perfusion on CEUS, and signs of local extension such as sinus invasion, perinephric spread, collecting system involvement, and renal vein or inferior vena cava tumor thrombus. A comparative method was used to evaluate how each modality contributes to the detection pathway in different patient groups, including patients with chronic kidney disease, contrast contraindications, and incidentally discovered small renal masses.

Results: The reviewed evidence demonstrated that RCC detection depends on a multimodality imaging strategy rather than a single universal technique. The practical sequence of imaging is determined by the clinical presentation, patient condition, availability of technology, and the degree of suspicion for malignancy. Several consistent findings emerged from the analysis.

First, conventional ultrasound remains an important entry point in the diagnostic pathway. It is widely accessible, rapid, noninvasive, and free of ionizing radiation. In everyday practice it is often the first method to reveal a renal mass, particularly in patients undergoing abdominal scanning for nonspecific pain, urinary symptoms, hypertension, or routine screening. Ultrasound is effective for differentiating simple cysts from clearly solid lesions and can identify larger exophytic masses, hydronephrosis, or gross distortion of renal contour. However, its diagnostic performance decreases for small lesions, isoechoic tumors, centrally located masses, and obese patients with poor acoustic windows. A normal ultrasound examination does

not reliably exclude a small RCC, especially if the lesion is endophytic or technically obscured. Thus, ultrasound is valuable for detection but limited for definitive characterization.

Second, multiphasic contrast-enhanced CT remains the principal imaging method for suspected RCC in most adult patients. CT combines broad availability, high spatial resolution, rapid acquisition, and excellent anatomic detail. Pre-contrast, corticomedullary, nephrographic, and excretory phase information allows the radiologist to assess enhancement, vascularity, calcifications, internal necrosis, hemorrhage, collecting system relationship, and extension beyond the kidney. In clear cell RCC, enhancement is often intense and heterogeneous, reflecting the tumor's hypervascular nature. Papillary RCC usually enhances less avidly and may appear relatively homogeneous and hypovascular. Chromophobe RCC can overlap with both patterns, which limits subtype prediction. Even so, measurable enhancement on multiphasic CT remains one of the most important imaging signs of solid malignant renal neoplasia. CT also performs well for evaluation of multifocal disease, regional adenopathy, contralateral renal lesions, and distant metastatic spread when the examination is extended appropriately.

Third, CT plays a central role not only in primary detection but also in staging. Accurate preoperative staging requires assessment of tumor size, relation to the renal sinus, penetration through the capsule, involvement of Gerota's fascia, venous tumor thrombus, and adrenal or lymph node extension. These elements strongly influence the surgical approach and prognosis. Tumors confined to the kidney may be suitable for nephron-sparing surgery, while large infiltrative masses or lesions with venous involvement may require radical nephrectomy or more complex oncological management. Therefore, the diagnostic value of CT lies in its ability to move beyond simple lesion detection and provide a near-complete map of disease extent. This makes

CT the backbone of radiological work-up in the majority of RCC cases.

Fourth, MRI has a major complementary role in RCC detection and characterization. MRI is especially useful when CT findings are equivocal, when iodinated contrast media are contraindicated, when renal function is impaired, or when superior soft tissue contrast is required. MRI helps detect enhancement in lesions that are difficult to classify on CT, and it can add important information regarding pseudocapsule, hemorrhagic contents, venous invasion, and complex cystic masses. Diffusion-weighted imaging may increase lesion conspicuity and provide indirect information about tumor cellularity, while chemical shift sequences can identify microscopic fat and assist in the differential diagnosis of selected masses. MRI is also valuable in evaluating tumor thrombus within the renal vein or inferior vena cava, where multiplanar capability and soft tissue contrast are advantageous. Although MRI does not eliminate overlap between RCC subtypes, it substantially improves characterization when CT alone is not definitive.

Fifth, contrast-enhanced ultrasound has emerged as a particularly important adjunct for indeterminate renal masses. CEUS enables real-time visualization of microvascular perfusion using purely intravascular microbubble contrast agents, without ionizing radiation and with a favorable safety profile in many patients with renal dysfunction. According to the reviewed literature, CEUS is especially helpful for clarifying whether a lesion truly enhances, distinguishing pseudotumors from solid neoplasms, evaluating septa and nodularity in cystic lesions, and characterizing masses that remain uncertain after baseline ultrasound or even after CT. Enhancement timing, wash-in, wash-out, and the degree of heterogeneity may support suspicion for malignancy. In practical terms, CEUS is most useful as a problem-solving tool rather than as a universal replacement for CT or MRI. Its limitations include operator dependence, restricted field of view, impaired assessment in deeply located or

obscured lesions, and inability to provide complete thoracoabdominal staging.

Sixth, one of the most important radiological problems in RCC detection is the evaluation of small renal masses. With the increasing use of cross-sectional imaging, many lesions smaller than 4 cm are now found incidentally. These masses include not only RCC, but also oncocytoma, lipid-poor angiomyolipoma, inflammatory lesions, and complex cystic neoplasms. Imaging may suggest malignancy, yet no single radiological sign is fully specific. Hyperenhancement favors clear cell RCC but can overlap with oncocytoma, low enhancement may suggest papillary RCC but can also be seen in some benign lesions. In these cases, imaging must be interpreted together with lesion morphology, growth pattern, patient age, renal function, and clinical context. The review confirms that imaging is excellent at identifying suspicious lesions and stratifying probability, but not always sufficient for final histological certainty.

Seventh, imaging findings contribute directly to decisions about surveillance, biopsy, ablation, and surgery. A Bosniak-classified cystic lesion with enhancing nodularity, a progressively enlarging enhancing cortical mass, or a lesion with venous extension strongly supports intervention. In contrast, a small stable lesion in a frail patient may be managed with active surveillance, especially when imaging suggests indolent behavior. Thus, the value of imaging extends beyond simple diagnosis, it supports individualized treatment planning. This point is particularly relevant in modern urological oncology, where overtreatment of benign or indolent renal masses should be minimized whenever possible.

Eighth, subtype-oriented imaging interpretation has become increasingly important. Clear cell RCC, the most frequent histological subtype, typically demonstrates hypervascular and heterogeneous enhancement with areas of necrosis, cystic degeneration, or intratumoral hemorrhage in larger tumors. Papillary RCC often presents as a more homogeneous, hypovascular lesion and can be less conspicuous at

corticomedullary phase CT, which creates a risk of underestimation if technique is suboptimal. Chromophobe RCC may show intermediate enhancement and a relatively well-circumscribed morphology, but considerable overlap persists. These patterns are clinically useful because they help the radiologist assign a probability of subtype, yet they cannot be considered absolutely diagnostic. Histopathology remains the reference standard when treatment decisions require certainty.

Ninth, cystic renal lesions represent another major area in which imaging determines patient management. Complex cystic masses are frequently detected incidentally and require careful assessment of septa, mural nodules, wall irregularity, and true enhancement. CT and MRI remain central to Bosniak-based classification, but CEUS can reveal subtle vascularized septa or nodules that may not be clearly appreciated on baseline ultrasound. This is particularly valuable for lesions that are borderline between categories or when MRI is unavailable. Because many cystic RCCs can be treated effectively when diagnosed early, accurate imaging characterization of cystic lesions has direct prognostic value.

Tenth, local extension and vascular invasion are decisive imaging findings in RCC. A tumor that extends into the renal vein or inferior vena cava changes the operative strategy, increases technical complexity, and has prognostic implications. CT is commonly used for this purpose, but MRI can be superior in defining the cephalad extent of thrombus, distinguishing bland thrombus from tumor thrombus in selected cases, and demonstrating the relationship between the thrombus and vessel wall. Likewise, imaging signs of perinephric spread, renal sinus invasion, or adrenal involvement help distinguish organ-confined disease from more advanced tumors. This staging information is one of the main reasons imaging is indispensable even after the lesion itself has already been detected.

Eleventh, imaging has substantial value in the differential diagnosis of RCC. Not all enhancing renal masses are carcinoma. Oncocytoma may mimic RCC on CT and MRI, angiomyolipoma without macroscopic fat can also appear suspicious, inflammatory pseudotumors and focal infections occasionally simulate neoplasia. In these difficult cases, the radiologist must integrate all available information rather than relying on a single sign. Lesion margin, growth direction, enhancement pattern, diffusion restriction, the presence or absence of a central scar, and clinical factors such as fever, known tuberous sclerosis, or prior malignancy all influence interpretation. When uncertainty remains high and management would change, image-guided biopsy becomes an important complementary step.

Twelfth, the literature also highlights the ongoing development of novel imaging techniques. Molecular imaging approaches such as PSMA-based tracers, sestamibi imaging, and other targeted methods are being investigated to improve lesion characterization and, in some settings, to distinguish oncocytoma from RCC or to assess metastatic disease biology. However, these techniques are not yet established as standard first-line tools for routine primary RCC detection. Their current role is promising but supplementary. For present-day clinical practice, multiphasic CT remains the central modality, MRI is the most important complementary cross-sectional method, and CEUS provides valuable targeted characterization in selected cases.

Finally, the reviewed data support a practical diagnostic algorithm. When a renal lesion is first seen on ultrasound, contrast-enhanced CT is usually the next step for confirmation and staging. When CT cannot be performed or yields equivocal results, MRI is recommended for further characterization. When the lesion remains indeterminate, particularly in patients with renal impairment or contraindication to standard contrast agents, CEUS offers an effective problem-solving alternative. This

stepwise, patient-tailored approach best reflects current radiological practice and ensures that RCC detection is both accurate and clinically useful. In this way, imaging serves as a bridge between incidental discovery and evidence-based treatment selection.

An additional practical advantage of imaging is its role in treatment selection for nephron-sparing surgery. Modern renal surgery increasingly depends on precise preoperative mapping of tumor location relative to the renal hilum, collecting system, and vascular pedicle. Cross-sectional imaging helps determine whether a tumor is predominantly exophytic or endophytic, whether it abuts the sinus fat, and whether there is a safe margin for partial nephrectomy. These details are not minor technical observations, they directly affect ischemia time, operative complexity, blood loss risk, and postoperative renal preservation. Therefore, imaging in RCC detection should also be understood as imaging for surgical planning.

Imaging is equally important in the follow-up setting after local treatment. Patients who undergo partial nephrectomy, ablation, or surveillance require radiological monitoring for local recurrence, residual enhancement, or interval growth. Knowledge of the expected postoperative appearance is essential to avoid misinterpretation. Scar tissue, postoperative fluid collections, and altered enhancement can mimic disease if the radiologist is unfamiliar with treatment history. CEUS may be useful after ablation to detect residual vascularized tumor, whereas CT and MRI remain essential when broader post-treatment assessment is required. This reinforces the idea that imaging in RCC is not limited to one diagnostic moment, but extends throughout the patient pathway.

Another relevant observation is the importance of technical quality in renal imaging protocols. Poor timing of contrast phases, respiratory motion, inadequate slice thickness, or incomplete renal coverage can significantly reduce sensitivity for small

lesions. Papillary tumors in particular may be underestimated when corticomedullary and nephrographic enhancement are not optimally captured. Likewise, MRI interpretation depends on correct sequence selection, including T1-weighted, T2-weighted, diffusion-weighted, and post-contrast acquisitions. The literature therefore supports standardized protocol design as an essential prerequisite for accurate RCC detection.

From a broader oncological perspective, imaging also contributes to prognostic estimation. Tumor size, local stage, necrosis, vascular invasion, and metastatic spread are all radiologically appreciable features linked to outcome. While radiology cannot replace pathology or molecular analysis, it provides an early noninvasive portrait of disease burden and likely clinical behavior. This makes imaging indispensable in multidisciplinary tumor boards, where radiologists, urologists, oncologists, and pathologists integrate findings into a unified treatment plan. In this way, the detection of RCC is not a narrow diagnostic act, but the starting point of coordinated oncological care.

Conclusion: Imaging is fundamental to the detection and initial evaluation of renal cell carcinoma. Conventional ultrasound remains useful for first-line identification of renal lesions, but in most patients definitive assessment requires cross-sectional imaging. Multiphasic contrast-enhanced CT is the primary modality for RCC detection because it provides robust lesion characterization together with local and distant staging. MRI is indispensable when CT is contraindicated or inconclusive and adds important value in soft tissue characterization and venous assessment. CEUS has become an increasingly important adjunct for indeterminate renal masses, especially in patients who cannot undergo routine contrast-enhanced CT. Therefore, the most effective strategy for RCC detection is a multimodality and patient-specific imaging pathway. Continued development of functional and molecular imaging may

further improve differentiation between benign and malignant renal masses and may enhance early diagnosis in the future.

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