EVALUATION OF RENAL MASSES WITH CONTRAST-ENHANCED ULTRASOUND

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Abstrac. The accurate evaluation of renal masses is essential for early diagnosis, appropriate clinical management, and improved patient outcomes. Contrast-enhanced ultrasound (CEUS) has emerged as a valuable, non-invasive imaging modality that provides real-time assessment of microvascular perfusion without the use of ionizing radiation or nephrotoxic contrast agents. This thesis investigates the diagnostic utility of CEUS in the characterization of renal masses.

The study focuses on the ability of CEUS to differentiate benign and malignant renal lesions based on enhancement patterns, vascular architecture, and wash-in/wash-out dynamics. Special attention is given to its role in identifying small renal masses, complex cystic lesions, and indeterminate findings detected by conventional imaging methods such as computed tomography (CT) and magnetic resonance imaging (MRI).

Keywords: renal masses, contrast-enhanced ultrasound, CEUS, renal cell carcinoma, imaging diagnostics, microvascularity, kidney tumors.

Relevance of the topic: The evaluation of renal masses remains one of the most important problems in modern diagnostic radiology because the growing availability of abdominal ultrasound, computed tomography, and magnetic resonance imaging has led to a steady increase in the incidental detection of focal renal lesions. A significant number of these masses are found in asymptomatic patients during routine check-ups or investigations performed for unrelated abdominal complaints. This epidemiologic shift has created a practical dilemma: the radiologist must not only detect the lesion but also determine, as early and as accurately as possible, whether it represents a harmless benign structure or a malignant tumor requiring active treatment. Such differentiation is critically important because renal masses encompass a broad pathologic spectrum, including simple cysts, hemorrhagic cysts, inflammatory lesions, angiomyolipoma, oncocytoma, multilocular cystic neoplasm, and different histologic subtypes of renal cell carcinoma.

Renal cell carcinoma is the most common malignant neoplasm of the kidney in adults, and early diagnosis strongly influences surgical strategy, nephron-sparing options, oncologic prognosis, and follow-up planning. However, not all renal masses with suspicious morphology are malignant, and not all malignant lesions behave identically. In daily clinical work, inaccurate lesion characterization can cause two opposite but equally undesirable consequences. On the one hand, benign lesions may be overcalled as cancer, exposing patients to unnecessary anxiety, biopsy, surgery, or loss of functioning renal parenchyma. On the other hand, subtle malignant masses may be underestimated, which delays treatment and increases the risk of local progression or metastatic spread. Therefore, improvement of renal mass characterization is not merely a technical imaging issue but a clinically meaningful step in personalized patient management.

Conventional B-mode ultrasound is often the first-line method in renal imaging because it is inexpensive, accessible, fast, repeatable, and free of ionizing radiation. It is very effective for detecting simple cysts and larger masses, but its diagnostic performance decreases when the examiner has to determine lesion vascularity, analyze complex cystic architecture, detect very small solid components, or separate true tumors from pseudotumoral lesions. Color Doppler may add some information, yet low-flow microvascular perfusion can remain undetected, especially in small masses or lesions with complex internal structure. Consequently, conventional ultrasound frequently identifies a lesion without fully solving the diagnostic problem.

Multiphasic CT and MRI are widely used as standard cross-sectional methods for characterization of renal masses. They provide valuable information about enhancement, local extent, adjacent organ involvement, venous invasion, and distant spread. Nevertheless, these methods also have limitations. CT requires ionizing radiation and iodinated contrast material, which may be problematic in patients with chronic kidney disease or contrast allergy. MRI offers excellent soft-tissue contrast, but it is more expensive, less available in some settings, technically longer, and can be limited by motion artifacts, claustrophobia, metallic implants, or gadolinium-related concerns in specific patient populations. These limitations have stimulated growing interest in diagnostic alternatives that can bridge the gap between screening ultrasound and full cross-sectional imaging.

Against this background, contrast-enhanced ultrasound has become an increasingly relevant modality. CEUS uses gas-filled microbubbles as intravascular contrast agents and allows continuous real-time visualization of lesion perfusion without nephrotoxicity and without radiation exposure. Its temporal resolution is superior to CT and MRI because the enhancement process is observed dynamically rather than

captured in only a few static phases. This makes CEUS particularly useful for analyzing early arterial enhancement, cortical wash-in, wash-out behavior, septal vascularity, mural nodules, pseudocapsule formation, and intralesional nonperfused necrotic zones. The method is especially valuable for indeterminate renal masses, complex cysts, small renal lesions, and cases in which CT or MRI findings remain equivocal.

Another reason for the current relevance of CEUS lies in the changing clinical concept of renal tumor management. Many small renal masses are now managed by active surveillance, minimally invasive ablation, or nephron-sparing surgery rather than by radical resection alone. Such approaches require a more refined pre-treatment imaging assessment. The clinician increasingly needs information not simply about the presence of a mass, but about its biologic behavior, perfusion characteristics, and the probability of malignancy. CEUS contributes to this modern decision-making model because it helps identify viable solid tissue, suspicious cystic components, and post-treatment residual vascularization. In addition, CEUS may reduce the need for repeated CT examinations during surveillance, thereby decreasing radiation burden in patients who require serial imaging. From the point of view of practical healthcare organization, CEUS is also important because it is relatively accessible, can be performed in real time by the radiologist, and can immediately influence the diagnostic algorithm during the same patient visit. In institutions where MRI access is limited or where rapid clarification of indeterminate findings is required, CEUS offers a cost-conscious and patient-friendly solution. Thus, the study of renal masses with contrast-enhanced ultrasound is highly актуal not only for academic radiology but also for routine clinical practice, especially in the context of early cancer detection, rational use of imaging resources, and preservation of renal function.

Aim of the study: The aim of this thesis is to assess the diagnostic role of contrast-enhanced ultrasound in the evaluation of renal masses, to determine the principal CEUS criteria that help distinguish benign from malignant lesions, and to define the practical place of this method in the contemporary imaging algorithm for focal renal pathology. Additional aims include analysis of CEUS utility in small renal masses and complex cystic lesions, evaluation of its significance in patients who cannot undergo contrast-enhanced CT or MRI without limitations, and systematization of those perfusion signs that most strongly influence diagnostic confidence and clinical management.

Materials and methods: The thesis is based on an analytical and descriptive radiologic approach that integrates contemporary literature data, accepted imaging principles, and structured interpretation of renal mass perfusion characteristics. The material of the work includes current scientific publications dedicated to CEUS in abdominal and urogenital imaging, practical diagnostic algorithms used for focal renal lesions, and comparative concepts relating CEUS findings to conventional ultrasound, CT, MRI, and histopathologic interpretation. The study is designed as a theoretical synthesis intended to summarize and systematize the role of CEUS in detection and characterizationofrenalmasses.
At the initial stage of the imaging pathway, each renal lesion is classified according to the way it is detected and according to baseline sonographic morphology. The basic features recorded on grayscale ultrasound include lesion size, localization, exophytic or endophytic growth, echogenicity, homogeneity, posterior acoustic phenomena, calcification, relation to the renal sinus, distortion of the contour, and presence of cystic or solid components. Particular attention is given to lesions that cannot be confidently labeled as simple cysts and to masses whose internal structure suggests complexity or possible vascularity. These lesions constitute the

main target group for further CEUS evaluation.
The CEUS examination is conceptually performed after intravenous administration of a microbubble ultrasound contrast agent under low mechanical index settings. This technical mode preserves microbubble integrity and allows prolonged real-time visualization of intravascular flow. Dynamic monitoring is carried out from the earliest cortical enhancement to the late phase. During the study, the examiner compares lesion enhancement with adjacent renal cortex, assesses the speed of wash-in, the pattern of vascular filling, the presence of homogeneous or heterogeneous perfusion, internal avascular areas, peripheral rim enhancement, septal enhancement, mural nodules, and the timing of wash-out. Because CEUS provides continuous observation rather than static snapshots, subtle temporal differences in perfusion are carefully noted.
For analytical purposes, renal masses in this thesis are divided into four principal diagnostic groups. The first group consists of non-neoplastic cystic lesions, including simple cysts and hemorrhagic or proteinaceous cysts. Their main CEUS criterion is the absence of internal contrast enhancement. The second group consists of complex cystic renal masses, where CEUS is used to evaluate the vascularity of the wall, septa, and intracystic nodules, thereby helping to stratify the lesion according to malignant potential. The third group includes solid renal masses such as renal cell carcinoma, angiomyolipoma with minimal fat, oncocytoma, and other less frequent tumors. In these cases, CEUS analysis focuses on tumor perfusion architecture, hyperenhancement or hypoenhancement relative to cortex, heterogeneity, necrotic areas, and wash-out kinetics. The fourth group includes pseudotumoral conditions and non-neoplastic focal abnormalities, such as focal pyelonephritis, infarction, compensatory hypertrophy, and prominent columns of Bertin, which may mimic tumors on conventional imaging.

The methodological comparison performed in this thesis places CEUS in relation to CT and MRI not as a competing universal modality but as a problem-solving imaging method. Comparative analysis emphasizes those clinical scenarios in which CEUS is particularly advantageous: patients with chronic kidney disease, hypersensitivity to iodinated contrast material, repeated follow-up needs, uncertain enhancement on CT or MRI, and indeterminate cystic masses requiring more precise vascular evaluation. In addition, the thesis evaluates the role of CEUS in the pre-biopsy setting, where identification of viable enhancing tissue can improve sampling accuracy and reduce the chance of nondiagnostic material caused by necrosis.

Special methodological attention is devoted to the interpretation of cystic renal lesions. In the diagnostic pathway described here, complex cysts are not judged solely by their appearance on grayscale ultrasound. Instead, the internal vascular behavior demonstrated on CEUS is treated as the key indicator of biologic relevance. Avascular thin septa and smooth walls favor lower-risk lesions, whereas irregular enhancing septa, nodularity, or wall thickening increase concern for malignancy. This approach reflects the broader clinical principle that renal cystic lesion management is guided by enhancement rather than morphology alone. Another important methodological aspect concerns small renal masses. Lesions less than 4 cm are frequently encountered in current practice and often represent an area of diagnostic uncertainty. For such masses, the thesis analyzes how CEUS can reveal microvascularity that is occult on conventional ultrasound and how this influences the differentiation of true tumors from pseudolesions. The method is also considered in follow-up after thermal ablation or partial nephrectomy, where demonstration of persistent or recurrent enhancement may indicate residual viable tumor.

The synthesis of results in this thesis is performed by descriptive comparison and radiologic interpretation. The focus is not only on whether CEUS detects enhancement, but also on how the specific enhancement pattern influences diagnostic reasoning. Thus, the materials and methods of the present work are designed to reflect real clinical decision-making, where CEUS is used as an advanced but practical technique for refinement of renal mass diagnosis and optimization of further management.

Results: The analysis of available radiologic evidence demonstrates that contrast-enhanced ultrasound significantly improves characterization of renal masses when compared with baseline ultrasound alone. The most consistent result is the high sensitivity of CEUS for detecting true lesion perfusion. Because the microbubble contrast agent remains strictly intravascular and enhancement is assessed continuously in real time, CEUS can demonstrate low-volume vascularity that may be invisible on grayscale imaging or insufficiently appreciated on color Doppler. This capability is particularly relevant in lesions that outwardly resemble complicated cysts but contain small enhancing septa or mural nodules indicative of neoplastic transformation.

A major result of the present synthesis concerns the differentiation of cystic lesions. Simple cysts reliably show complete absence of enhancement on CEUS, thereby allowing a benign diagnosis with high confidence. Hemorrhagic or proteinaceous cysts may appear complex on grayscale imaging, yet if no enhancing septa or nodules are detected on CEUS, the lesion can be interpreted as nonvascular and therefore likely benign. In contrast, complex cystic masses with irregular wall enhancement, thick vascular septa, or enhancing intracystic projections are far more suspicious. CEUS is especially valuable in these cases because the method depicts the vascularized soft-tissue elements that determine malignant potential. As a result,

CEUS contributes to more accurate risk stratification of cystic renal lesions and may reduce both false reassurance and unnecessary overtreatment.

The findings related to solid masses are also substantial. Renal cell carcinoma commonly demonstrates contrast enhancement that differs from adjacent cortex in both intensity and temporal behavior. Many RCCs show rapid and heterogeneous wash-in, disorganized internal vascular architecture, focal nonenhancing necrosis, and relatively early wash-out. Such features are strongly suggestive of malignancy, especially when combined with irregular contour and solid tissue composition. Clear cell RCC often appears hypervascular in early phases, while papillary RCC may demonstrate lower and more homogeneous enhancement. Chromophobe tumors may show variable behavior. Although there is overlap between histologic subtypes, CEUS consistently distinguishes vascular solid neoplasms from avascular cystic lesions and improves the level of suspicion for malignancy in indeterminate masses.

One important result is that CEUS performs particularly well in the evaluation of small renal masses. These lesions frequently pose a diagnostic challenge because subtle enhancement may not be confidently appreciated on standard ultrasound, and the size of the lesion may make Doppler analysis unreliable. CEUS can reveal microvascularity, peripheral pseudocapsule, tiny necrotic areas, and internal heterogeneity in lesions only a few centimeters in diameter. Such information may influence whether the patient is directed toward active surveillance, biopsy, ablative therapy, or nephron-sparing surgery. In this respect, CEUS supports the modern management strategy of individualized treatment rather than uniform radical intervention.

The analytical results also show that CEUS is highly useful in the differentiation of tumors from pseudotumors and non-neoplastic focal abnormalities. A

hypertrophied column of Bertin or persistent fetal lobulation can simulate a cortical mass on baseline imaging, but on CEUS these structures usually enhance synchronously and symmetrically with the adjacent parenchyma, supporting a benign anatomic variant. Focal pyelonephritis may demonstrate patchy or reduced perfusion, while renal infarction typically shows sharply demarcated wedge-shaped nonenhancing defects. Such patterns differ from the irregular tumoral enhancement seen in RCC and help prevent diagnostic errors that could otherwise lead to unwarranted oncologic work-up.

Another important outcome concerns patients with contraindications or limitations for CT and MRI contrast studies. Since microbubble contrast agents used in CEUS are not nephrotoxic and are eliminated mainly through the lungs, CEUS provides a safe and practical alternative in patients with reduced renal function. This is of major clinical significance because renal impairment is not uncommon in the same patient population in which renal masses are detected. By making reliable perfusion analysis possible without worsening renal function, CEUS expands diagnostic access for vulnerable patients. The absence of radiation further supports its use in repeated examinations and follow-up studies.

The thesis findings further indicate that CEUS has a valuable role in intervention planning and post-treatment assessment. Before biopsy, CEUS can identify the most viable and vascularized tumor portions, helping avoid sampling from necrotic areas and thereby improving diagnostic yield. After ablative therapy, successful treatment is suggested by the absence of enhancement in the ablation zone, whereas focal residual enhancement raises concern for persistent viable tumor. Similarly, after partial nephrectomy, CEUS may help clarify suspicious findings in the renal remnant when conventional ultrasound is inconclusive. These applications extend the usefulness of CEUS beyond initial diagnosis and into longitudinal oncologic management.

From the standpoint of comparative imaging, the results suggest that CEUS is not a full substitute for CT or MRI staging. The method has a limited field of view and is less suitable for comprehensive assessment of regional lymph nodes, venous tumor thrombus above the visualized segment, distant metastases, and large infiltrative tumors involving adjacent structures. However, within its intended scope—namely lesion characterization—CEUS shows excellent performance. In many cases it functions as the most informative intermediate step between baseline ultrasound and more extensive cross-sectional imaging.

The results also reveal important practical limitations. CEUS remains operator dependent and requires training in both acquisition and interpretation. Diagnostic quality may be reduced in deeply located lesions, obese patients, and situations with poor acoustic window due to overlying bowel gas or rib shadowing. Some benign and malignant solid tumors can show overlapping enhancement characteristics, which means CEUS should be interpreted within the broader clinical and radiologic context. Nevertheless, these limitations do not diminish its value; rather, they define the conditions under which the method should be used most appropriately.

Taken together, the results of the present thesis indicate that CEUS markedly increases diagnostic confidence in renal mass evaluation. It is especially powerful for confirming absence or presence of vascularity, refining assessment of complex cysts, detecting microperfusion in small masses, distinguishing pseudotumors from neoplasms, guiding biopsy, and monitoring response after minimally invasive treatment. Therefore, CEUS occupies an important and increasingly evidence-based place in the contemporary imaging pathway for renal masses.

Conclusion: Contrast-enhanced ultrasound is a highly informative and clinically

meaningful imaging method in the evaluation of renal masses. Its key diagnostic advantage is the ability to visualize lesion microvascularity in real time, which significantly improves differentiation between benign cystic lesions, pseudotumoral conditions, and vascularized neoplasms. The thesis confirms that CEUS is particularly valuable in indeterminate renal lesions, complex cystic masses, and small renal tumors, where the demonstration of enhancement directly affects diagnostic interpretation and further management.

The findings show that CEUS increases confidence in identifying suspicious malignant features such as irregular enhancing septa, mural nodules, heterogeneous vascularity, internal necrotic nonperfusion, and early wash-out relative to the adjacent renal cortex. At the same time, the method allows reliable confirmation of benignity in lesions without enhancement and helps recognize pseudolesions whose perfusion pattern matches normal renal parenchyma. In this way CEUS reduces both underdiagnosis of significant tumors and overtreatment of harmless findings.

An additional strength of CEUS is its safety and practicality. The method does not expose the patient to ionizing radiation, can be repeated as needed, and is particularly useful in patients with impaired renal function because microbubble agents are not nephrotoxic. These characteristics make CEUS an attractive diagnostic option for serial follow-up, active surveillance, post-treatment monitoring, and clarification of equivocal findings on other imaging modalities. Its role in biopsy planning and assessment after local ablative therapy further expands its clinical relevance.

At the same time, CEUS should be viewed as a complementary rather than universally replacing method. Its limitations include operator dependence, restricted panoramic assessment, and lower suitability for complete oncologic staging in advanced disease. Therefore, the optimal diagnostic strategy is a multimodal one in which CEUS is integrated with conventional ultrasound, CT,

MRI, and histopathologic verification whenever indicated. Thus, evaluation of renal masses with contrast-enhanced ultrasound represents a modern and effective direction in radiologic diagnostics. Broader implementation of CEUS in routine practice can improve early detection of clinically significant renal tumors, optimize the diagnostic pathway, reduce unnecessary invasive procedures, and support more individualized preservation-oriented treatment of patients with focal renal lesions.

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