Available Online: 12 June 2025 DOI: 10.54254/3049-5458/2025.23857

Application of multiparameter Magnetic Resonance Imaging in diagnosis and staging of Prostate Cancer

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Abstract. Prostate cancer, as an epithelial malignant tumor occurring in the prostate, has already become one of the most common malignant tumors among the male population globally. Traditional diagnostic methods, such as PSA testing and biopsy, have certain limitations in practical application and are difficult to provide relatively intuitive and comprehensive diagnostic results. This article mainly reviews the current application status of multiparametric Magnetic Resonance Imaging (mpMRI) technology in the diagnosis and staging of prostate cancer. The study has found that, relying on its unique advantages, the mpMRI technology can not only conduct a detailed and comprehensive diagnosis of prostate cancer but also demonstrate extremely high accuracy in tumor staging. With the research results of this study, medical staff can implement the diagnostic process for prostate cancer patients from a more refined dimension, thereby significantly improving the diagnostic efficiency and minimizing the adverse impacts caused to patients due to misdiagnosis and missed diagnosis. These results will contribute to reducing the burden on the healthcare system and promoting the improvement of the public's health level.

Keywords: mpMRI, Prostate Cancer, diagnosis, staging

1. Introduction

In recent years, the incidence rate of Prostate Cancer (PCa) has been increasing year by year, and it ranks first among malignant tumors of the male urinary system in China [1]. Early screening and diagnosis can improve the prognosis and enhance the quality of life of patients [2]. The role of multiparametric Magnetic Resonance Imaging (mpMRI) technology in the diagnosis and staging of the prostate has gradually become prominent. Multiparametric magnetic resonance imaging can simultaneously provide multifaceted tissue information, such as morphology, function, metabolism, etc. It can conduct more comprehensive and accurate disease diagnosis, condition assessment, and differential diagnosis. Moreover, it has no radiation and has high soft tissue resolution. Through the exploration in this article, we can conduct a more comprehensive and refined diagnosis for prostate cancer patients, which is helpful for more efficient diagnosis and reduces the harm caused by misdiagnosis and missed diagnosis. These research achievements will contribute to reducing the burden on the healthcare system and promoting the improvement of the public's health level.

2. The current status of prostate cancer incidence

The incidence of PCa varies significantly across regions, ethnicities, and age groups. Globally, there are significant regional differences. In European and American countries, PCa is among the most common malignancies in men, with African American men having the highest incidence rates worldwide. In contrast, the incidence in Asian countries such as China and Japan has traditionally been lower. However, due to the increasing westernization of lifestyles, the incidence in these regions has been gradually rising.

In China, there are approximately 115,426 new PCa cases and 51,094 deaths annually, making it the sixth most common male malignancy and the leading cancer of the urinary system. With the aging population, the total number of PCa cases is expected to continue rising. The five-year survival rate in China is 69.2%, considerably lower than the 93% rate in developed countries like Japan. Notably, while metastatic PCa accounts for only 5% - 6% of new cases in Europe and the U.S., this figure reaches 54% in China, indicating a higher proportion of late-stage diagnoses [1].

Age is also a key factor. PCa incidence rises significantly with age, typically occurring after age 50, with a peak between 70 and 80 years old. Although mortality rates in Western countries remain relatively high, they have decreased in recent years due to improvements in screening and treatment. In Asian countries, while mortality remains lower, it is also trending upward.

Clinically, several methods are used for PCa screening and diagnosis. Digital Rectal Examination (DRE) has low sensitivity for early-stage PCa and is influenced by physician experience, making it subjective. Prostate-Specific Antigen (PSA) testing, although widely used, lacks specificity. Conditions such as prostatitis or benign prostatic hyperplasia can also elevate PSA levels, resulting in false positives and unnecessary follow-ups. Conversely, early-stage PCa may not showed elevated PSA level, leading to false-negative results.

Prostate biopsy, while standard, is invasive and carries risks of bleeding and infection. It also has limitations in detecting all cancerous lesions, especially in PCa cases. Today, mpMRI has emerged as a key tool for the initial assessment of suspected PCa prior to biopsy. The Prostate Imaging-Reporting and Data System (PI-RADS) version 2.1 provides a standardized framework for MRI acquisition and reporting, improving diagnostic consistency across medical centers and enhancing early detection of PCa [2].

3. The concept of multiparametric magnetic resonance imaging

mpMRI of the prostate is transforming the diagnosis and staging of prostate cancer by providing high-resolution images with excellent tissue contrast. The basic principle of mpMRI relies on the different signal characteristics exhibited by various tissues in magnetic resonance imaging. It obtains detailed tissue information by using multiple imaging sequences and parameter settings. mpMRI operates through strong magnetic fields and the electromagnetic properties of hydrogen atoms to generate signals and construct images. Prostate mpMRI typically combines different imaging sequences, including T1-Weighted Imaging (T1WI), T2-Weighted Imaging (T2WI), Diffusion-Weighted Imaging (DWI), and Dynamic Contrast-Enhanced MRI (DCE-MRI). These sequences collectively provide detailed information on the prostate's anatomical structure, as well as the location, size, and shape of tumors, and their relationship with surrounding tissues [3].

T1WI is useful for visualizing the overall anatomical structure of the prostate, including the prostate capsule and its surrounding tissues. It helps distinguish regions such as the central gland and peripheral zone. T1WI is particularly helpful in detecting hemorrhage and calcification within lesions and is used to identify prostate and seminal vesicle bleeding, delineate the prostate gland contour, and detect lymph node or bone metastases, especially after the administration of Gadolinium-Based Contrast Agents (GBCA) [4]. T2WI offers high signal contrast between different tissue types, enabling clear visualization of the prostate's internal anatomy. It is especially sensitive to early-stage prostate lesions and small tumor nodules. Even in the absence of obvious morphological changes, T2WI can reveal subtle signal abnormalities indicative of cancer, facilitating early detection. Additionally, T2WI can helps localize tumors accurately and assess their size and extent, which is crucial for planning treatment strategies. A study by Isaak, Sprinkart, and Katemann demonstrated that Deep Learning (DL)-based reconstruction of low-resolution T2-weighted Turbo Spin Echo (TSE) sequences can accelerate image acquisition, enhance quality, and maintain consistency with the traditional sequence in PI-RADS grading, which is helpful for the early and non-invasive diagnosis of prostate cancer [5].

DWI measures the movement of water molecules within tissues. In PCa, the high cell density and reduced extracellular space restrict water diffusion, producing lower signals. Researchers at the Affiliated Hospital of Fudan University found that both mono-exponential and kurtosis parameter Kapp may serve as an excellent predictor of tumor aggressiveness, and the use of diffusion kurtosis imaging in clinical practice is recommended [6]. Therefore, DWI is high sensitive for detecting small cancer foci that may be missed by T1WI and T2WI, and is particularly valuable in patients with slightly elevated PSA level or egative digital rectal exams. As a functional imaging tool, DWI also has applications beyond oncology, such as in stroke diagnosis and nerve fiber tracking [7].

Dynamic Contrast-Enhanced Imaging (DCE-MRI) involves rapid, continuous scanning after the intravenous injection of contrast agents, allowing real-time observation of the constant agent's uptake, peak enhancement, and washout in prostate tissue. Therefore, it has a high sensitivity for the early detection of prostate cancer. Since the angiogenesis of cancerous tissues occurs earlier than morphological changes, it can also detect tiny cancer foci that are difficult to find conventional imaging methods, which helps to improve the early diagnosis rate of prostate cancer. DCE can clearly show the boundary and extent of the tumor, help determine whether the tumor invades surrounding tissues and organs, and provide a basis for formulating a reasonable treatment plan. Dynamic contrast-enhanced imaging provides information about tissue blood perfusion and vascular permeability by observing the uptake and clearance of the contrast agent within the tissues.

By integrating this multiparametric information, multiparametric prostate magnetic resonance examination can more accurately detect prostate cancer, evaluate the location, size, extent, and invasiveness of the tumor, help distinguish between clinically significant and insignificant prostate cancer, provide positioning guidance for prostate biopsy, and monitor the recurrence and progression of the tumor after treatment [8].

4. The role in prostate cancer diagnosis

Recently, mpMRI has emerged as a promising imaging tool for prostate assessment, allowing clinicians to localize possible cancerous lesions with high precision. This information facilitates targeted prostate biopsies, limiting the number of unnecessary

procedures while improving the accuracy of tumor grading. Consequently, mpMRI enables the development of more individualized and effective treatment strategies for patients. Importantly, mpMRI is more likely to detect Clinically Significant Prostate Cancers (csPCa) while avoiding detection of small, indolent tumors. Meanwhile, a negative mpMRI provides the patient excellent assurance that they do not harbor a clinically significant PCA. Reports have shown mpMRI to have a negative predictive value of 95 % for clinically significant cancer when performed before biopsy [9].

The main methods for detecting and locating prostate cancer lesions include T2WI, DWI, DCE-MRI, and magnetic resonance spectroscopy imaging. Prostate cancer often appears as low-signal nodules in the peripheral zone on T2WI, as the cancerous tissue destroys the normal prostate gland structure, creating a contrast with the surrounding normal tissue, which aids in the detection and localization of the tumor. For example, on T2WI images, one can clearly see relatively well-defined low-signal areas in the prostate peripheral zone, suggesting the possible presence of cancerous lesions. DWI images are created by detecting the diffusion movement of water molecules in tissues, and due to the high cell density of prostate cancer tissue, water molecule diffusion is restricted, appearing as a high signal on DWI, with a reduced Apparent Diffusion Coefficient (ADC) value. This technique is sensitive to the early detection of prostate cancer, capable of identifying some small lesions that are difficult to detect on T2WI. In dynamic contrast-enhanced imaging, after intravenous injection of a contrast agent, the dynamic changes of the contrast agent in the prostate tissue are observed. Prostate cancer tissue is rich in blood supply, and the contrast agent flows in early and quickly, appearing as early enhancement on DCE-MRI images. By combining sequences such as T2WI and DWI, the cancerous lesions can be more accurately localized, and the extent of tumor invasion can be determined. Multiparametric magnetic resonance imaging can also be used to differentially diagnose benign and malignant lesions of the prostate. In the case of benign lesions: Benign Prostatic Hyperplasia (BPH) often appears as high-signal nodules within the transitional zone on T2WI, with clear boundaries and a complete low-signal capsule around them. Prostatitis may manifest as overall or localized signal abnormalities on T2WI, generally without significant nodular changes. Benign prostatic tissue appears isointense or slightly hyperintense on DWI, with higher ADC values. In the case of BPH nodules, they typically show relatively high signal on ADC maps, with ADC values usually greater than those of malignant lesions. In benign prostatic tissue, the Choline (Cho) level is normal or mildly elevated, while the Citrate (Cit) level is higher, resulting in lower Cho peaks and higher Cit peaks on Magnetic Resonance Spectroscopy (MRS), with a normal or mildly elevated Cho/Cit ratio. Therefore, MRS can also be used for diagnosis. In the case of malignant lesions, prostate cancer often appears as low-signal nodules in the peripheral zone on T2WI, usually with irregular shapes, blurred boundaries, and sometimes breaking through the capsule to invade surrounding tissues, causing signal changes in the surrounding tissues. Due to the high cell density and restricted diffusion of water molecules, prostate cancer tissue appears as a significantly high signal on DWI, with markedly reduced ADC values. On the ADC map, it presents as a low signal, which is significantly different from the surrounding normal tissue and benign lesions. In MRS detection, due to the high cell density and restricted diffusion of water molecules, prostate cancer tissue presents as a distinct high signal on DWI, with significantly reduced ADC values. On the ADC map, it presents as a low signal, which is significantly different from the surrounding normal tissue and benign lesions.

5. The role in prostate cancer staging

mpMRI plays a significant role in evaluating the extent of local invasion of prostate cancer tumors. Firstly, it can determine the invasion of the capsule. On T2WI, the normal prostate capsule appears as a continuous low-signal ring, and if the prostate cancer invades the capsule, it will manifest as an interruption in the continuity of the capsule, local elevation, or irregularity. On DWI, high signal intensity can also be seen at the site of the invaded capsule, and when combined with a decrease in ADC values, it can more accurately determine the invasion. Secondly, it can detect involvement of the seminal vesicles. The seminal vesicles appear as high signal intensity on T2WI, and when they are invaded by the tumor, the high signal intensity on T2WI is replaced by low signal intensity, and early enhancement can be seen on DCE-MRI. If mpMRI shows abnormal signals in the seminal vesicles, combined with clinical symptoms and other examinations, it can be determined whether the seminal vesicles have been infiltrated by the tumor. It can also assess whether the surrounding tissues are invaded. mpMRI can observe the invasion of surrounding tissues by prostate cancer, such as the rectum, bladder, and pelvic floor muscles. If the tumor invades the rectum, on T2WI it can manifest as thickening of the rectal wall and abnormal signal intensity, and on DWI, it appears as high signal intensity with a decrease in ADC values. Prostate cancer has the potential for distant metastasis, such as osteoblastic changes, lymph node metastasis, liver metastasis, and lung metastasis, among others. mpMRI can be used for certain screenings. For instance, osteoblastic changes. On T1WI, metastatic lesions appear as low signal; on T2WI, the signal can vary, being low, high, or mixed. On DWI, metastatic lesions show a distinct high signal, with a decreased ADC value. For example, when a lesion with low signal on T1WI, high signal on T2WI, and high signal on DWI is found in the vertebral body of the spine, combined with clinical information, bone metastasis can be highly suspected. Or lymph node metastasis, where metastatic lymph nodes appear as high signal on DWI and have a decreased ADC value. During contrast-enhanced scanning, they may show heterogeneous enhancement. For example, lymph nodes found in the pelvis or retroperitoneum with a short diameter greater than 10mm, high signal on DWI, and heterogeneous enhancement on contrast-enhanced scanning suggest the possibility of metastatic lymph nodes. Liver and lung metastases can also be screened. Liver metastases appear as low signal on T1WI, high signal on T2WI, and high signal on DWI, with a decreased ADC value. When multiple nodules with these signal characteristics appear in the liver, prostate cancer liver metastasis is considered possible. Lung metastases appear as nodular high signal on T2WI and high signal on DWI, with a decreased ADC value. “Magnetic resonance imaging (MRI) is currently considered an effective imaging modality for diagnosing prostate cancer.” A study analyzing the imaging and clinical data of 42 untreated newly diagnosed prostate cancer patients found

that "Amino Proton Transfer (APT) quantitative parameters are closely related to bone metastasis in prostate cancer and have good predictive value for the metastatic risk of newly diagnosed prostate cancer patients." APT technology belongs to MRI molecular imaging technology, and the quantitative parameter APT mean value obtained can quantitatively reflect the cellular protein molecular situation. In predicting the risk of prostate cancer bone metastasis, the APT mean value has a high specificity when used independently, and the predictive ability is best when combined with other parameters [10].

6. Conclusion

This article primarily investigates the role of mpMRI in the diagnosis and staging of prostate cancer. By introducing the principles of mpMRI and its various sequences and advantages, it is evident that multiparametric magnetic resonance imaging offers significant benefits for the diagnosis and treatment of prostate cancer, integrating early diagnosis, precise staging, effective guidance, and scientific evaluation. At the level of early diagnosis, mpMRI accurately captures the fine structures and signal abnormalities of the prostate through multi-sequence, multi-parameter imaging, with T2-weighted imaging and diffusion-weighted imaging revealing even the smallest cancerous lesions. For tumor staging, it relies on excellent soft tissue resolution and contrast agent perfusion monitoring to clearly display the capsule and the invasion of surrounding tissues, thus defining the disease progression. Post-treatment, mpMRI can objectively assess therapeutic outcomes by monitoring changes in tumor volume and signals, providing a solid basis for subsequent adjustments in treatment plans, and offering comprehensive support for precise diagnosis and treatment of prostate cancer. Currently, mpMRI has shown good diagnostic efficacy in liver and breast cancer. In liver cancer diagnosis, mpMRI can improve early diagnostic rates and precisely evaluate tumor characteristics, also guiding interventional treatments. In breast cancer diagnosis, it can perform preoperative staging assessments and monitor the efficacy of neoadjuvant chemotherapy. mpMRI has high sensitivity, capable of detecting some occult lesions that are difficult to detect by clinical palpation and other examinations, thus preventing missed diagnoses. The main future research focus for mpMRI is its integration with artificial intelligence technology to enhance diagnostic efficacy and expand application scenarios. It will not only be limited to disease diagnosis but will also play a greater role in treatment decision-making, therapeutic evaluation, follow-up monitoring, and overall management of diseases, providing more comprehensive information support for personalized medicine

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