New Strategies in Prostate Cancer: Prostate-Specific Membrane Antigen (PSMA) Ligands for Diagnosis and Therapy

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Abstract

Key issues for prostate cancer patients are the detection of recurrent disease and the treatment of metastasized cancer. Early detection is a major challenge for all conventional imaging modalities. Furthermore, therapy of patients with hormone-resistant tumor lesions presents a major clinical challenge. Because the prostate-specific membrane antigen (PSMA) is frequently overexpressed in prostate cancer, several PSMA-targeting molecules are under development to detect and treat metastatic castration-resistant prostate cancer (mCRPC). mCRPC represents a situation where cure is no longer achievable and novel therapeutic approaches for palliation and increase of survival are needed. In this article, we discuss the recent development for noninvasive detection of recurrent disease and therapy of mCRPC with corresponding PSMA-targeted radioligands. Clin Cancer Res; 22(1); 9–15. ©2016 AACR.

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Learning Objectives

Upon completion of this activity, the participant should be able to understand the background and pharmacokinetics of PSMA ligands for PET/CT, estimate the value of PSMA-based imaging in comparison to choline-based imaging, assess the value of PSMA targeting for diagnosis and therapy, and estimate the effects and side effects of endoradiotherapy with PSMA ligands.

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Background

Prostate cancer is the most common cancer in men in Europe and the United States. Early detection of localized disease results in a 5-year survival rate of nearly 100%. However, metastasized tumors lead to dramatically reduced survival rates. Early detection not only leads to a decrease in mortality, but also to overdagnosis and overtreatment, which has a negative impact on the quality of life of men with prostate cancer (1). The variability of clinical course and high prevalence of microscopic disease (2, 3) create the need for risk-adapted strategies to optimize patient care. These strategies cover a whole spectrum from active surveillance to aggressive treatment. In that respect patient-adapted staging is essential for better individual outcomes and requires sensitive and specific imaging of prostate cancer, including intraprostatic disease as well as local and distant metastases. Furthermore, if active surveillance becomes a management option in low-grade disease, a sensitive method of monitoring changes in tumor volume, location, and aggressiveness would potentially eliminate the need for repetitive biopsies, thereby enabling a more advanced temporal evaluation in vivo.

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Prostate-specific antigen (PSA) kinetics has been used so far to assess the risk in first-line treatment failures, but the method is known to be unreliable for active surveillance (4), because even a stable PSA during the first 2 years after diagnosis does not preclude the formation of distant metastases and the possibility of lethal cancer (5–7).

Because distinct changes at the molecular level are responsible for the biologic behavior of tumors, trials to validate biomarkers that identify patients at risk are under way. Genomics data may lead to a better prediction of tumor behavior; however, it still has not achieved widespread acceptance, because biopsies are required (3). In contrast, noninvasive imaging offers the possibility to perform repeated measurements of tumor progression and biologic alteration, which can be used for individual patient staging and guiding the optimal treatment option. In essence, monitoring changes in disease burden at the whole-body level may offer the best means of patient management.

PET/CT with choline tracers has been widely used for the staging and detection of recurrent disease; however, numerous studies report a low sensitivity and specificity of these tracers, especially in patients with low PSA levels (8–11). Consequently, improved imaging of prostate cancer is necessary. One novel promising method is PET imaging with anti-1-amino-3-fluorocyclobutane-1-carboxylic acid (18F-FACBC), a new synthetic amino acid. Recent evaluations by Nanni and colleagues present evidence that this tracer is superior when compared with choline-PET/CT (12). However, there is still a high demand for novel imaging and therapy procedures targeting structures associated with aggressive disease, which could improve the detection rate and offer options for the treatment of metastatic disease, especially in the case of metastatic castration-resistant prostate cancer (mCRPC). Because curative approaches no longer exist for patients with mCRPC and also the use of androgen receptor axis-targeted drugs, such as abiraterone and enzalutamide, inevitably leads to resistance against these agents, new isotope-based pharmaceuticals offer the chance of symptom relief and/or prolongation of survival.

On the Horizon
Prostate-specific membrane antigen as a target
Several biologic characteristics make prostate-specific membrane antigen (PSMA), also known as folate hydrolase I or glutamate carboxypeptidase II, an outstanding target for drug development. PSMA is a type II transmembrane protein with glutamate-carboxypeptidase activity and shows a significant overexpression on prostatic cancer cells, including advanced-stage prostate carcinomas (13, 14), but a low expression in normal tissues. Thus, PSA can be considered as ideal for developing small and low-molecular-weight targeted radiopharmaceuticals with fast blood clearance and low background activity. Furthermore, upon ligand binding PSMA is internalized via clathrin-coated pits and subsequent endocytosis (15), resulting in an effective transportation of the bound molecule into the cells. This leads to an enhanced uptake, deposit, and retention in the tumor, resulting in high image quality for diagnosis and a high local dose for therapeutic applications (Fig. 1). Several studies report that PSMA expression levels increase according to the stage and grade of the tumor (14–17). Moreover, nearly all adenocarcinomas of the prostate show PSMA expression in the majority of primary and metastatic lesions (17, 18). Therefore, a variety of PSMA-targeted radioligands for diagnosis and therapy has been developed (see selected refs. 19–43). Table 1 summarizes selected radiopharmaceuticals for the diagnosis and therapy of prostate cancer.

Diagnostics
Clinical trials with the radiolabeled anti-PSMA monoclonal antibody J591 have shown improved targeting of prostate cancer (41, 43). Although antibodies offer potential for tumor targeting, their effectiveness as diagnostic radiopharmaceuticals is limited by a long biologic half-life and poor tumor penetrability, particularly for bone metastases. There are promising approaches that may overcome these limitations, such as combining antibodies with the longer-lived PET radionuclides 89Zr and 64Cu (42) or using single chain fragments or the anti-PSMA minibody 89Zr-Df-IAB2M as smaller variants of the humanized J591. Apart from diagnosis, however, antibodies directed against PSMA may have an adjuvant therapeutic impact as they are able to recruit cells of the immune system.

Early work on the development of small molecule inhibitors, mimicking the endogenous substrate N-acetyl-l-aspartyl-l-glutamate (NAAG), normally cleaved by N-acetylated alpha-linked acidic dipeptidase (NAALADase) or glutamate carboxy-peptidase II, identified a number of candidates as described by several groups (44–46). Ultimately, the identification of the structural

Figure 1. After binding to PSMA, the ligand (A, antibody; B, small molecule) is internalized into the cell. Because the clearance of small molecules is very fast, this leads to an excellent contrast during the first 60 minutes after injection of the molecule.
and functional (47, 48) homology between NAALADase and PSMA opened the prospect of using these small molecules in the targeted treatment and imaging of prostate cancer. Subsequent to these reports several groups have reported on the development of small-molecule inhibitors of PSMA labeled with $^{123}$I, $^{99m}$Tc, $^{18}$F, $^{11}$In, and $^{68}$Ga, based on the structural motifs of various NAALADase inhibitors (25–37, 39, 49, 50).

The first high-affinity small-molecule inhibitors of PSMA, $^{123}$I-MIP-1072, and $^{123}$I-MIP-1095, were introduced into the clinic in 2008. In men with metastatic prostate cancer, SPECT/CT using these molecules demonstrated the ability to rapidly detect lesions in soft tissue, bone, and the prostate gland as early as 1 to 4 hours after injection (30). $^{123}$I-MIP-1072 was subsequently evaluated in an animal model of prostate cancer under chemotherapy and clearly demonstrated that tumor uptake is directly proportional to the viable tumor mass, providing the potential to track changes in response to therapy.

Glu-NH-CO-NH-Lys-(Ahx)-$^{68}$Ga(HBED-CC) ($^{68}$Ga-PSMA-11) as a $^{68}$Ga-labeled PSMA-targeted radioligand became one of the most successful radiopharmaceuticals with respect to on-site availability (32) and clinical application. In a retrospective analysis in 319 patients, at least one lesion was detected in 82.8% of patients, at least one suspicious lesion was identified in 30 patients using choline-PET/CT. The higher detection rate in $^{68}$Ga-PSMA-ligand PET/CT concerning prostate cancer–suspicious lesions was significant ($P = 0.004$). All lesions detected by $^{18}$F-fluoromethylcholine-PET/CT were also seen by $^{68}$Ga-PSMA-ligand PET/CT. In $^{68}$Ga-PSMA-ligand, PET/CT SUV$_{max}$ was clearly (>10%) higher in 62 of 78 lesions (79.1%) and tumor-to-background ratio was clearly (>10%) higher in 74 of 78 lesions (94.9%) when compared with $^{18}$F-fluoromethylcholine-PET/CT. Therefore, $^{68}$Ga-PSMA-PET/CT detects prostate cancer–suspicious relapses and metastases with improved contrast when compared with standard $^{18}$F-fluoromethylcholine-PET/CT, especially at low PSA levels (31).

Up to now, a systematic analysis of PSMA ligand PET/CT performance in patients with primary tumors prior to standardized surgery and standardized pathologic evaluation has not been done. Such an analysis would result in reliable data concerning the sensitivity and specificity of PSMA ligand imaging for tumor and lymph node metastasis detection.

### Treatment

**Theranostics in endoradiotherapy: see what you treat.** Given that a cell surface associated molecule is overexpressed in the tumor compared with normal tissues, therapeutically active doses can be delivered to the target tissue with diminished side effects. Depending on the radionuclide used radiolabeled drugs additionally allow imaging. The attractive feature is that patients may first be identified as possible candidates for endoradiotherapy after labeling of the carrier molecule with a γ or positron emitter. Upon positive findings, the same molecule can be used for therapy by labeling it with an α- or β-particle emitter. Further advantages of endoradiotherapy over traditional therapies can be expected from the cross-fire effect induced by the β particles originating from the binding site. These particles lead to the destruction of multiple
Four patients had PSA stabilization whereas 21 of 35 patients had evidence of biologic activity. PSA stabilization was observed by week 12. Disease responses with 90% and 40% decrease in the size of pelvic and retroperitoneal lymphadenopathy. In 6 patients, dose-limiting myelosuppression; up to 3 doses of 30 mCi/m² could be safely administered. Based on PSA criteria, 14 patients showed progressive disease (PSA increase of ≥25%) after treatment whereas 21 of 35 patients had evidence of biologic activity. Four patients had ≥50% PSA declines lasting 3–8 months, and 16 patients had PSA stabilization (<25% increase from baseline) lasting at least 28 days. The median duration of PSA stabilization was 60 days, with a range of 28 to 601 days.

Subsequently, a dual-center phase II study of the safety and efficacy of 124I-MIP-1095 was performed in 47 patients. Dosimetry scans were done in 16 patients with mCRPC, which demonstrated PSMA-avid lesions on imaging. The patients received a single therapeutic activity of 131I-MIP-1095 (mean activity 4.8 GBq, range 2.0–7.2 GBq). In 14 patients, white blood cell counts fell below the normal range after therapy (10 patients with grade 1, 3 with grade 2, and 1 with grade 3 toxicity). However, 5 of these 14 patients had levels below normal prior to therapy (4 grade 1, 1 grade 2). Erythrocyte counts fell below the normal range at nadir in 21 patients, with 17 patients having lower values prior to therapy. With respect to platelets, 11 patients had a reduction in counts below normal after therapy (8 grade 1, 1 grade 2, and 2 grade 3), and 1 had a value below normal (grade 2) prior to therapy. The changes in hematologic parameters were not related to the activity administered. The onset of the myelosuppression occurred within 6 weeks after treatment with a variable time to recovery, in some cases requiring up to 3 to 6 months for recovery. White blood cells typically recovered within several weeks, whereas platelets required several months to recover.

In some patients, evidence of nonhematologic transient side effects was found: 7 patients reported having a slight to moderate xerostomia and in 1 patient mucositis was detected. All reported recovery from side effects after 3 to 4 weeks. This latter finding is likely due to the high level of radiopharmaceutical accumulation in these organs and the estimated absorbed doses.

After treatment, 3 out of 13 (23.1%) patients with bone pain reported complete resolution of bone pain, and 8 (61.5%) reported a decrease in pain severity. In the remaining 2 patients the outcome is unknown. In 60.7% of patients a decline in serum PSA levels of ≥50% was observed; 7 (25%) had more than a 75% drop in PSA, 10 (35.7%) had a drop between 50% and 75%, 2 (7.1%) between 25% and 50%, and 2 (7.1%) between 0% and 25% (54). One patient showed a long-lasting complete response by serum PSA value and by radiographic imaging. In 4 patients an increase of PSA was observed. As with the hematologic parameters, the changes in PSA value were not related to the activity administered. In the 19 patients showing a more than 25% decrease in PSA, the median time to PSA progression was 126 weeks.
days (range 62–469 days). A decrease in PSA was associated with a decrease in number and/or intensity of the lesions visualized on the posttherapeutic PET/CT scan with 68Ga-labeled Glu-NH-CO-NH-Lys(Ahx)-HBED-CC (PSMA11; Fig. 2).

Although 131I-MIP-1095 confirms that this class of PSMA inhibitors may be effective for radiotherapeutic applications, the use of β-particle emitting radionuclides such as 177Lu or 90Y would be preferable, given the advantages of energy, availability, and the potential for on-site labeling via kit formulations. To that end, PSMA inhibitors have been developed, which include chelators for labeling with radiometals commonly used for radiodiagnostics and radiotherapeutic applications. The most potent DOTA-conjugates of PSMA inhibitors exhibit affinity constants which compare favorably with the compounds that have already entered the clinic and shown excellent tumor uptake and retention. The versatility of DOTA facilitates the use of β-emitters, such as 177Lu and 90Y, and α-emitters, such as 225Ac, with minimal γ emissions that can be readily and safely used in the clinic (49, 55, 56).

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Conception and design: U. Haberkorn, J.W. Babich, M. Eisenhut
Development of methodology: J.W. Babich, M. Eisenhut
Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): U. Haberkorn
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Study supervision: U. Haberkorn

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