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.

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The members of the planning committee have no real or apparent conflicts of interest to disclose.

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-[18F]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, PSMA 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 JS91 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 JS91. 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

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**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.

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Table 1. Radiopharmaceuticals used for diagnosis and therapy of prostate cancer

<table>
<thead>
<tr>
<th>Tracer</th>
<th>Principle</th>
<th>Application</th>
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<tr>
<td>11C-acetate</td>
<td>Glucose metabolism</td>
<td>Diagnosis, PET</td>
</tr>
<tr>
<td>11C-choline, 15F-choline, 18F-methylcholine, 18F-ethylcholine</td>
<td>Fatty acid de novo synthesis</td>
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<td>99mTc-MIP-1404</td>
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<tr>
<td>111In-MIP-1072, 99mTc-MIP-1095</td>
<td>Amino acid transport; synthetic leucine analogue</td>
<td>Diagnosis, PET</td>
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<tr>
<td>18F-FACBC</td>
<td>PSA ligand; antibody</td>
<td>Diagnosis, PET</td>
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<tr>
<td>18F-DCEBC</td>
<td>PSA ligand; antibody</td>
<td>Diagnosis, PET</td>
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<tr>
<td>68Ga-PSMA-HBED-CC (PSMA-11)</td>
<td>PSA ligand; small-molecule inhibitor</td>
<td>Therapy</td>
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<tr>
<td>90Y-J591</td>
<td>PSA ligand; antibody</td>
<td>Therapy</td>
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<td>177Lu-J591</td>
<td>PSA ligand; small-molecule inhibitor</td>
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<td>111In-MIP-1466</td>
<td>PSA ligand; small-molecule inhibitor</td>
<td>Therapy</td>
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<tr>
<td>177Lu-PSMA-617</td>
<td>PSA ligand; small-molecule inhibitor</td>
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Abbreviation: SPECT, single photon emission computed tomography.

and functional (47, 48) homology between NAAALADase 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 123I, 99mTc, 18F, 111In, and 68Ga, based on the structural motifs of various NAAALADase inhibitors (25–37, 39, 49, 50).

The first high-affinity small-molecule inhibitors of PSMA, 123I-MIP-1072, and 123I-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). 123I-MIP-1072 was subsequently evaluated in an animal model of prostate cancer under chemotherapy and clearly demonstrated that tumor uptake is direct proportional to the viable tumor mass, providing the potential to track changes in response to therapy.

Glu-NH-CO-NH-Lys-(Ahx)-[68Ga(HBED-CC)] (68Ga-PSMA-11) as a 68Ga-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 the patients (33). Tumor detection was positively associated with PSA level and androgen deprivation therapy. Gleason score and tumor-to-background ratio 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 18F-fluoromethylcholine-PET/CT. All lesions detected by 18F-fluoromethylcholine-PET/CT were also seen by 68Ga-PSMA-ligand PET/CT. In 68Ga-PSMA-ligand, PET/CT SUVmax 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 18F-fluoromethylcholine-PET/CT. Therefore, 68Ga-PSMA-PET/CT detects prostate cancer–suspicious lesions and metastases with improved contrast when compared with standard 18F-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
cells in the neighborhood of the target-expressing cell and may compensate for heterogeneous target expression in tumors. These results are in contrast to nonradioactive targeting treatment, where usually only the cells binding the therapeutic molecule are destroyed. Further enhancement of therapeutic effects is caused by the radiation-induced bystander effect (RIBE). RIBE describes a situation where cells, which have not been directly exposed to the ionizing radiation, behave as if they have been exposed: they die or show chromosomal instabilities or other abnormalities. Although the exact mechanism of RIBE is not fully understood, there is evidence that chemical signaling processes transmit information from irradiated cells to neighboring cells (53).

PSMA-targeted radioimmunotherapy. J591 is a second-generation mAb that recognizes the extracellular portion of PSMA. J591 has been the subject of several clinical studies using various radioisotopes. Both $^{90}$Y- or $^{177}$Lu-labeled J591 have been the focus of independent phase I trials in men with mCRPC (20–24).

In the $^{90}$Y-J591 phase I trial (21), 29 patients received therapeutic doses of 5, 10, 15, 17.5, and 20 mCi/m$^2$ $^{90}$Y-J591. Dose-limiting toxicity was seen at 20 mCi/m$^2$, with 2 patients experiencing thrombocytopenia with non–life-threatening bleeding episodes requiring platelet transfusions. The 17.5-mCi/m$^2$ dose level was determined to be the maximum tolerated dose (MTD). Two patients treated at the 20-mCi/m$^2$ dose level exhibited 85% and 70% declines in PSA lasting 8 and 8.6 months, respectively, prior to returning to pretreatment values. In addition, these 2 patients had objective measurable disease responses with 90% and 40% decrease in the size of pelvic and retroperitoneal lymphadenopathy. In 6 patients, PSA stabilization was observed by week 12.

In the $^{177}$Lu-J591 phase I trial, 35 patients received J591 radiolabeled with doses of $^{177}$Lu ranging from 10 mCi/m$^2$ to 75 mCi/m$^2$ (22). Of the 3 patients at the 75-mCi/m$^2$ dose level, 1 experienced dose-limiting (grade 4) thrombocytopenia and 1 experienced dose-limiting neutropenia that lasted for 6 days. The 70-mCi/m$^2$ dose level was determined to be the MTD. Treatment was allowed after hematologic recovery. Repeated dosing at 45 to 60 mCi/m$^2$ 6 to 12 weeks after the initial dose resulted in dose-limiting myelosuppression; up to 3 doses of 30 mCi/m$^2$ could be safely administered. Based on PSA criteria, 14 patients showed progressive disease (PSA increase of $\geq$25%) after treatment whereas 21 of 35 patients had evidence of biologic activity. After treatment, 3 out of 13 (23.1%) patients with bone pain 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 $\geq$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 days, with a range of 28 to 601 days.

Subsequently, a dual-center phase II study of the safety and efficacy of $^{177}$Lu-J591 was performed in 47 patients with progressive mCRPC (24). Fifteen patients received 65 mCi/m$^2$, and 17 received 70 mCi/m$^2$. All patients experienced reversible hematologic toxicity, with grade 4 thrombocytopenia occurring in 46.8% (29.8% received platelet transfusions) without significant hemorrhage; 25.5% experienced grade 4 neutropenia with 1 episode of febrile neutropenia. The phase I MTD (70 mCi/m$^2$) resulted in more than 30% PSA declines (46.9% vs. 13.3%, $P = 0.048$) and longer survival (21.8 vs. 11.9 months, $P = 0.03$), but also more grade 4 hematologic toxicity and platelet transfusions. No serious nonhematologic toxicity occurred. Overall, 59.6% of the patients experienced any PSA decline following their single treatment, with 36.2% experiencing a $\geq$30% decline and 10.6% experiencing a $\geq$50% decline in PSA.

Therapy with PSMA inhibitors. The results of the initial clinical investigation of $^{123}$I-MIP-1072 and $^{123}$I-MIP-1095 led to the evaluation of these radioiodinated ligands as potential PSMA-targeted radiotherapeutics when radiolabeled with $^{131}$I (25,26,30).

Dosimetry scans were done in 16 patients with $^{123}$I-MIP-1095 PET/CT (54). Based on the biodistribution data obtained from the $^{124}$I-MIP-1095 PET images, the absorbed dose for $^{124}$I-MIP-1095 was calculated using the physical decay characteristics of $^{124}$I (software OLINDA/EXM). The organs receiving the highest absorbed doses following administration of $^{124}$I-MIP-1095 are the salivary glands [mean dose 4.6 mGy/MBq, followed by the liver (1.5 mGy/MBq) and the kidneys (1.5 mGy/MBq)]. This leads to an estimated absorbed dose for the injected therapy activities (mean dose 4.8 GBq, range 2.0–7.2 GBq) for the salivary glands of 9.2 to 33.3 Gy. Liver radiation doses fall in the range of 2.9 to 10.6 Gy. The kidneys received a total absorbed dose between 2.9 and 10.4 Gy. The mean total whole-body absorbed dose was 0.38 mGy/MBq resulting in 0.76 to 2.7 Gy based on the injected activities. Lymph node and bone metastases were exposed to estimated absorbed doses up to 300 Gy (34).

Therapy was done in 25 men with mCRPC, which demonstrated PSMA-avid lesions on imaging. The patients received a single therapeutic activity of $^{131}$I-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 quite 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 $\geq$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 days.
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 radiodiagnostic and radiotherapeutic applications. The most potent DOTA-conjugates of PSMA inhibitors exhibit affinity constants which compare favorably with the compounds that already have 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).

Authors’ Contributions
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
Writing, review, and/or revision of the manuscript: U. Haberkorn, M. Eder, K. Kopka, J.W. Babich, M. Eisenhut
Study supervision: U. Haberkorn

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