68Ga-labeled ODAP-Urea-based PSMA Agents in Prostate Cancer: First-in-human Imaging of an Optimized Agent

Xiaojiang Duan

Peking University First Hospital

Zhen Cao

Peking University First Hospital

Hua Zhu

Peking University Cancer Hospital & Institute

Chen Liu

Peking University Cancer Hospital & Institute

Xiaojun Zhang

The First Medical Center of Chinese PLA General Hospital

Jinming Zhang

The First Medical Center of Chinese PLA General Hospital

Yanan Ren

Peking University Cancer Hospital & Institute

Futao Liu

Peking University Cancer Hospital & Institute

Xuekang Cai

Peking University First Hospital

Xiaoyi Guo

Peking University Cancer Hospital & Institute

Zhen Xi

Nankai University

Martin G.Pomer

Johns Hopkins Medical Institutions

Zhi Yang

Peking University Cancer Hospital & Institute

Yan Fan (✉ fanyan980618@sina.com)

Peking University First Hospital

Xing Yang

Peking University First Hospital

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Supporting information

⁶⁸Ga-Labeled ODAP-Urea-based PSMA Agents in Prostate Cancer:

First-in-human Imaging of An Optimized Agent

Xiaojiang Duan¹, Zhen Cao¹, Hua Zhu², Chen Liu², Xiaojun Zhang³, Jinming Zhang³, Ya'nan Ren², Futao Liu², Xuekang Cai¹, Xiaoyi Guo², Zhen Xi⁴, Martin G. Pomper⁵, Zhi Yang^{2,*}, Yan Fan^{1,*}, Xing Yang^{1,6,*}

¹Department of Nuclear Medicine, Peking University First Hospital, Beijing, 100034, China.

²Department of Nuclear Medicine, Peking University Cancer Hospital & Institute, Beijing 100142, China.

³Department of Nuclear Medicine, the First Medical Center of Chinese PLA General Hospital, Beijing 100853, China.

⁴State Key Laboratory of Elemento-Organic Chemistry and Department of Chemical Biology, National Pesticide Engineering Research Center, Nankai University, Tianjin, 300071, China.

⁵Russell H. Morgan Department of Radiology and Radiological Science, Johns Hopkins Medical Institutions, Baltimore, MD 21287, USA.

⁶Institute of Medical Technology, Peking University Health Science Center, Beijing, 100191, China

Corresponding Author:

Xing Yang, Tel: 86 10 83572928; Email: yangxing2017@bjmu.edu.cn

Yan Fan, Tel: 86 10 83572791; E-mail: fanyan980618@sina.com; fanyan@bjmu.edu.cn

Zhi Yang, Tel: 86 10 88196196; Email: pekyz@163.com

Xiaojiang Duan, Zhen Cao and Hua Zhu contribute equally to this work.

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1. Preparation of the ligands

General

All solvents and chemicals purchased from commercial sources were analytical grade or better and were used without further purification. The final products and key intermediates were characterized with mass spectrometry (MS). High performance liquid chromatography (HPLC) analysis was performed using a Venusil MP C18 4.60 × 150mm² column (Bonna-Agela Technologies, Tianjin, China) on a FL-LC010G chromatography system (Bonna-Agela Technologies, Tianjin, China) with solvent gradient A (water with 0.1% trifluoroacetic acid) and gradient B (acetonitrile with 0.1% trifluoroacetic acid) at a flow rate of 0.8 mL/min. The analytical HPLC condition was gradient of 5–95% B over 5 min and 95% B for another 10 min, and the retention times were reported. Preparative HPLC purifications were performed using a Phenomenex C18 Luna 10.0 × 250 mm² column on a FL-H050G preparative chromatography system (Bonna-Agela Technologies, Tianjin, China). The products were eluted using eluent A (water with 0.1% trifluoroacetic acid) and eluent B (acetonitrile with 0.1% trifluoroacetic acid) at a flow rate of 4 mL/min.

Synthesis of PSMA ligands P117-126

All the ligands were synthesized via solid-phase synthesis which was performed according to Fmoc peptide synthesis protocol. The synthesis cycle consisted of: i) Fmoc cleavage: 20% piperidine in *N,N*-dimethylformamide (DMF), ii) DMF washings, iii) coupling, and iv) DMF washings. The resin was treated with 2 mL dichloromethane (DCM) for 5 min three times and 2 mL DMF for 5 min three times before used. The resin was washed thoroughly before it was incubated with HBTU-preactivated amino acid, amino acid derivatives or *tris*-tBu-DOTA. DDE was cleaved by 2% hydrazine hydrate/DMF for 3 min twice. Cleavage from the solid support was performed with trifluoroacetic acid (TFA)/water/triisopropylsilane (95/2.5/2.5, vol/vol/vol) over 3h at room temperature. The products were purified by HPLC. The synthesis routes of P117-126 were shown in **Figure S1**.

Figure S1. Synthesis of **P117-126**. a: 20% piperidine in DMF deprotection, and then DMF solutions of Fmoc-a-OH, HBTU, HOBT and DIPEA; b: 20% piperidine in DMF deprotection, and then DMF solutions of Fmoc-b-OH, HBTU, HOBT and DIPEA; c: 20% piperidine in DMF deprotection, and then DMF solutions of Fmoc-c-OH, HBTU, HOBT and DIPEA; d: 20% piperidine in DMF deprotection, and then DMF solutions of **12**, HBTU, HOBT and DIPEA; e: 20% piperidine in DMF deprotection, and then DMF solutions of DOTA (2-(4,7,10-tris(2-(tert-butoxy)-2-oxoethyl)-1,4,7,10-tetraazacyclododecan-1-yl)acetic acid), HBTU, HOBT and DIPEA; f: trifluoroacetic acid/triisopropylsilane/water.

Compound **12** used by **P117-126** was synthesized according to the procedures shown in **Figure S2**. Benzyl 2-bromoacetate (**6**, 3.44 g, 15 mmol) and *tert*-Butyl 4-hydroxybenzoate (**7**, 2.43 g, 12.5 mmol) were dissolved in DMF (20 mL). Potassium carbonate (2.76 g, 20 mmol) was added to the solution. The mixture was stirred at 60 °C for 5 h. The reaction mixture was filtered and washed with DCM (100 mL). After the solvent was removed under vacuum, **8** (3.7 g, 86%) was obtained after silica gel flash column chromatography. The obtained **8** was dissolved in DCM (10 mL) and TFA (10 mL), and stirred at room temperature for 5 h. After the solvent was removed under vacuum, **9** was obtained. **9** (3.1 g, 10.8 mmol), 1-(3-dimethylaminopropyl)-3-ethylcarbodiimide hydrochloride (EDCI, 2.74 g, 14.3 mmol) and *N*-hydroxysuccinimide (NHS, 1.65 g, 14.3 mmol) were dissolved in DMF (50 mL) and the mixture was stirred at room temperature for 12 h. After the solvent was removed under vacuum, **10** (1.18 g, 28%) was obtained after silica gel flash column chromatography. **10** (1.18 g, 3.1 mmol) and (*S*)-*tert*-Butyl 6-Amino-2-(3-((*S*)-1-(*tert*-butoxy)-3-(2-(*tert*-butoxy)-2-oxoacetamido)-1-oxopropan-2-yl)-ureido) hexanoate (1.33g 2.57mmol) (*J. Med. Chem.* 2020, 63, 3563-3573) were dissolved in DMF (20 mL) and *N,N*-diisopropylethylamine (DIPEA) was added to the solution. The solution was stirred at room temperature for 12 h and after

the solvent was removed under vacuum, **11** (1.95 g, 82%) was obtained after silica gel flash column chromatography. **11** (700 mg, 0.89 mmol) and 10% dry Pd/C (50 mg) were mixed in MeOH (20 mL) under H₂ and stirred at room temperature for 12 h. After filtration, the solvent was removed under vacuum and **12** (500 mg, 81%) was obtained after silica gel flash column chromatography as a colorless oil. The MS data of all the key compounds were shown as follows (**Table S1**)

Figure S2. Synthesis of **12**. a: K₂CO₃, DMF, 60 °C; b: TFA, DCM; c: EDCI, NHS, DMF; d: (*S*)-*tert*-Butyl 6-Amino-2-(3-((*S*)-1-(*tert*-butoxy)-3-(2-(*tert*-butoxy)-2-oxoacetamido)-1-oxopropan-2-yl)-ureido)hexanoate, DMF, DIPEA; e: Pd/C, H₂, MeOH.

Synthesis of PSMA ligands P136-P144

The synthesis routes of the P136-144 were shown in **Figure S3**, with procedures similar to P117. The resin **13** was prepared from the key intermediate **21** as shown in **Figure S4**. Triphosgene (122 mg, 0.41 mmol) was dissolved in anhydrous DCM (30 mL) at -10 °C. To the solution, a mixture of **17** (500 mg, 1.229 mmol) and Et₃N (428 µL, 3.07 mmol) in anhydrous DCM (15 mL) was added over 30 min. The mixture was stirred at -10 °C for 2 h, and then a solution of compound **18** (354 mg, 1.229 mmol) (*J. Med. Chem.* 2020, 63, 3563-3573) and Et₃N (206 µL, 6.38 mmol) in anhydrous DCM (20 mL) was added. The reaction was stirred for another 1 h. After the solvent was removed under vacuum, **19** (614mg, 73%) was obtained after silica gel flash column chromatography as a colorless oil. A mixture of **19** (614 mg, 0.89 mmol) and 10% dry Pd/C was stirred in MeOH (30 mL) under H₂ for 12 h at room temperature. The reaction mixture was filtered and washed with MeOH (10 mL) and DCM (10 mL). The solvent was removed under vacuum to get **20** (410 mg, 83%) as a colorless oil and **20** was used for next step without further purification. **20** (410 mg, 0.735 mmol) was dissolved in 1,4-dioxane/H₂O (20 mL, 2.5/1, vol/vol). NaHCO₃ (252 mg, 3 mmol) and Fmoc-

Cl (228 mg, 0.882 mmol) were added to the solution and stirred for 10 min at room temperature. The reaction mixture was filtered and extracted with ethyl acetate (10 mL). After the solvent was removed under vacuum, **21** (290 mg, 59%) was obtained after silica gel flash column chromatography. 2-CTC resin (1 g) was added to DCM (10 mL) and the solution was stirred for 1h. After the solvent was removed, **21** (290 mg, 0.43 mmol) and DMF/DCM (10 ml, 1/1, vol/vol) were stirred for 3 h at room temperature. DCM/MeOH/DIPEA (10/10/1, vol/vol/vol) was used four times for blocking the excess reactive sites on 2-CTC resin. Finally, 1.2 g of **13** was obtained. The MS data of all the key compounds were shown as follows (**Table S1**)

Figure S3. Synthesis of **P136-144**. a: 20% piperidine in DMF deprotection, and then DMF solutions of Fmoc-a-OH, HBTU, HOBT and DIPEA; b: 20% piperidine in DMF deprotection, and then DMF solutions of Fmoc-b-OH, HBTU, HOBT and DIPEA; c: 20% piperidine in DMF deprotection, and then DMF solutions of DOTA (2-(4,7,10-tris(2-(tert-butoxy)-2-oxoethyl)-1,4,7,10-tetraazacyclododecan-1-yl)acetic acid), HBTU, HOBT and DIPEA; d: trifluoroacetic acid/triisopropylsilane/water.

Figure S4. Synthesis of **13**. a: DCM, Et₃N, triphosgene; b: Pd/C, H₂, MeOH; c: Fmoc-Cl, NaHCO₃, 1,4-dioxane, H₂O; d: 2-CTC resin, DMF, DCM, MeOH, DIPEA.

Table S1. Results of the identification of compounds by LC-MS.

Compound	Sum formula	<i>R</i> _t (HPLC analysis, min)	Yield of chemical synthesis	[M]	
				(calc.)	(found)
12	C ₃₃ H ₅₀ N ₄ O ₁₂	----	81.0%	694.34[M+H] ⁺	695.40
P117	C ₅₁ H ₇₇ N ₁₁ O ₂₁	5.853	14.2%	1179.53[M-H] ⁻	1178.40
P120	C ₆₀ H ₈₆ N ₁₂ O ₂₂	6.188	12.9%	1365.56[M+K] ⁺	1365.80
P122	C ₅₆ H ₈₀ N ₁₂ O ₂₂	6.062	19.0%	1311.51[M+K] ⁺	1311.75
P123	C ₆₄ H ₈₀ N ₁₂ O ₂₂	6.373	13.3%	1407.52[M+K] ⁺	1407.60
P124	C ₆₀ H ₈₂ N ₁₂ O ₂₂	6.238	12.3%	1361.53[M+K] ⁺	1361.65
P125	C ₆₅ H ₈₉ N ₁₃ O ₂₃	6.220	12.1%	1458.58[M+K] ⁺	1458.85
P126	C ₆₅ H ₈₉ N ₁₃ O ₂₃	6.202	12.3%	1458.58[M+K] ⁺	1458.60
21	C ₃₅ H ₄₆ N ₄ O ₁₀	----	57.8%	683.33[M+H] ⁺	683.40
P136	C ₄₉ H ₇₀ N ₁₀ O ₁₇	6.240	28.8%	1071.50[M+H] ⁺	1071.70
P137	C ₄₉ H ₆₄ N ₁₀ O ₁₇	6.273	44.4%	1065.45[M+H] ⁺	1065.65
P141	C ₄₅ H ₆₁ N ₁₀ O ₁₇	6.280	44.1%	1179.29[M+K] ⁺	1178.75
P143	C ₅₁ H ₆₆ N ₁₀ O ₁₇	6.395	34.4%	1129.42[M+K] ⁺	1128.90
P144	C ₄₅ H ₆₄ N ₁₀ O ₁₇	6.160	36.0%	1055.41[M+K] ⁺	1054.85

2. PSMA inhibition results of the ligands tested

Figure S5. Inhibition curves of P117-P144 and PSMA617 using a fluorescence-based NAALADase assay.

3. Radiolabeling yield and Log *P* of ⁶⁸Ga-labeled compounds

Radiolabeling: ⁶⁸GaCl₃ was obtained from a ⁶⁸Ge/⁶⁸Ga generator (maximum production 1.85 GBq, ITG, Germany). The preparation of ⁶⁸Ga-labeled compounds was carried out according to the following general procedure. After optimization, 30 µg of each ligand was incubated with a mixture of 1.0 mL ⁶⁸GaCl₃ (0.05 N HCl) eluent with radioactivity of 185-370 MBq and 65 µL sodium acetate (1 mol/L) at 85-90 °C for 10 min. The product was purified by a Sep-Pak® Light C18 cartridge (Waters, Milford, Massachusetts, USA) and the ⁶⁸Ga-labeled compound was obtained by eluting the cartridge with 0.6 mL 80% ethanol. After diluting with saline and passing through a 0.2 µm sterile filter (Merck Millipore, Darmstadt, Germany), the formulation was applied to the imaging study. The radiochemical purity (RCP) of ⁶⁸Ga-labeled compounds was analyzed by radio-HPLC (Shimadzu LC-20A, Japan; Flow-Count, Eckert&Ziegler, Germany).

Table S2. RCPs before and after purified and Log *P* values of ⁶⁸Ga-labeled compounds.

⁶⁸ Ga-Labeled compounds	RCPs before purified (repeat times)	RCPs after purified	Log <i>P</i>
[⁶⁸ Ga]Ga-P117	92%-95% (3)	>98%	-2.15 ± 0.17
[⁶⁸ Ga]Ga-P120	90%-95% (3)	>98%	-2.48 ± 0.10
[⁶⁸ Ga]Ga-P122	90%-96% (3)	>98%	-1.05 ± 0.09
[⁶⁸ Ga]Ga-P123	89%-93% (3)	>98%	-1.22 ± 0.06
[⁶⁸ Ga]Ga-P124	90%-94% (3)	>98%	-1.87 ± 0.04
[⁶⁸ Ga]Ga-P125	91%-95% (3)	>98%	-1.10 ± 0.05
[⁶⁸ Ga]Ga-P126	90%-95% (3)	>98%	-0.79 ± 0.08
[⁶⁸ Ga]Ga-P136	91%-96% (3)	>98%	-2.62 ± 0.30
[⁶⁸ Ga]Ga-P137	92%-97% (>10)	>99%	-2.48 ± 0.18
[⁶⁸ Ga]Ga-P141	90%-96% (3)	>98%	-1.19 ± 0.24
[⁶⁸ Ga]Ga-P143	91%-96% (3)	>98%	-1.46 ± 0.08
[⁶⁸ Ga]Ga-P144	92%-97% (3)	>98%	-1.84 ± 0.07
⁶⁸ Ga-PSMA-617	92%-98% (5)	>99%	-2.00 ± 0.27

4. MicroPET imaging studies and biodistribution

^{68}Ga -P117

^{68}Ga -P120

^{68}Ga -P122

^{68}Ga -P124

^{68}Ga -P123

^{68}Ga -P125

^{68}Ga -P126

^{68}Ga -P136

^{68}Ga -P137

^{68}Ga -P141

^{68}Ga -P143

^{68}Ga -P144

Figure S6. Whole-body coronal slices from MicroPET imaging of Balb/c nu mice bearing 22Rv1 tumor xenografts (n = 4).

Table S3. Biodistribution of [^{68}Ga]Ga-P137 in Balb/c nu mice bearing PSMA-positive 22Rv1 tumors (mean $\pm$ SD, n = 4, %ID/g)

Tissues	[^{68}Ga]Ga-P137				[^{68}Ga]Ga-PSMA-617
	30 min	60 min	120 min	60 min blocked	60 min
Heart	0.87 $\pm$ 0.50	0.37 $\pm$ 0.08	0.29 $\pm$ 0.04	0.41 $\pm$ 0.11	0.22 $\pm$ 0.12
Liver	0.92 $\pm$ 0.16	0.52 $\pm$ 0.13	0.48 $\pm$ 0.09	0.63 $\pm$ 0.10	0.34 $\pm$ 0.05
Lung	2.13 $\pm$ 0.70	1.00 $\pm$ 0.26	0.55 $\pm$ 0.08	1.03 $\pm$ 0.37	0.50 $\pm$ 0.10
Kidney	26.00 $\pm$ 17.86	6.04 $\pm$ 2.16	3.57 $\pm$ 1.03	1.77 $\pm$ 0.68**	5.17 $\pm$ 1.37
Spleen	1.06 $\pm$ 0.16	0.58 $\pm$ 0.17	0.35 $\pm$ 0.02	0.57 $\pm$ 0.25	0.39 $\pm$ 0.10
Stomach	0.54 $\pm$ 0.22	0.26 $\pm$ 0.12	0.18 $\pm$ 0.06	0.33 $\pm$ 0.24	0.17 $\pm$ 0.08
Muscle	0.71 $\pm$ 0.20	0.30 $\pm$ 0.20	0.19 $\pm$ 0.09	0.45 $\pm$ 0.10	0.13 $\pm$ 0.05
Large intestine	0.71 $\pm$ 0.14	0.61 $\pm$ 0.37	0.68 $\pm$ 0.31	0.51 $\pm$ 0.07	0.32 $\pm$ 0.18
Small intestine	0.63 $\pm$ 0.15	0.35 $\pm$ 0.12	0.20 $\pm$ 0.04	0.64 $\pm$ 0.10	0.15 $\pm$ 0.01
Tumor	5.69 $\pm$ 1.11	6.43 $\pm$ 0.98	6.91 $\pm$ 2.07	1.13 $\pm$ 0.33**	3.41 $\pm$ 1.31
Brain	0.11 $\pm$ 0.04	0.08 $\pm$ 0.03	0.06 $\pm$ 0.02	0.08 $\pm$ 0.04	0.05 $\pm$ 0.02
Blood	2.24 $\pm$ 0.87	0.91 $\pm$ 0.17	0.71 $\pm$ 0.06	1.00 $\pm$ 0.14	0.49 $\pm$ 0.13
Tumor/Muscle	8.74 $\pm$ 3.80	26.97 $\pm$ 13.39	44.42 $\pm$ 21.32	2.65 $\pm$ 1.16	29.61 $\pm$ 14.54
Tumor/Blood	2.94 $\pm$ 1.51	6.73 $\pm$ 1.48	9.62 $\pm$ 2.42	1.19 $\pm$ 0.36	6.97 $\pm$ 2.24

**P: Data showed significant different from [^{68}Ga]Ga-P137 without blocking at 60 min post-injection, $P < 0.01$.

5. Stability of [^{68}Ga]Ga-P137

Figure S7. Stability of [^{68}Ga]Ga-P137. (A) HPLC patterns of [^{68}Ga]Ga-P137 in saline and in 5% HSA at 4 h. (B) HPLC patterns of [^{68}Ga]Ga-P137 in tumor, blood, kidney and urine at 30 min post-injection.

6. Toxicity test

In order to verify the toxicity of DOTA-ODAP ligand, we conducted a toxicity test on P137 according to the Chinese Pharmacopoeia (2020 edition). 18-22g Kunming mice were selected and randomly grouped, 5 mice as the test group and 3 mice as the control group, and the weights of the mice were recorded before the test. The experimental group was injected with 0.5 mg/0.5 ml P137 solution (25 mg/kg, 167,000 times the dose administered to humans) through the tail vein of mice, and the control group was injected with the same volume of saline. The mice were observed for 2 days including diet, respiration, activity, defecation, skin and pain sensation and other indicators. In order to verify the toxicity of ^{68}Ga -P137, 5 Kunming mice (18-22 g) were used in the test with 3 mice as the control group, and the weights of the mice were recorded before the test. The experimental group was injected with 37 MBq/0.2 ml ^{68}Ga -P137 solution (1233MBq/kg, 330 times the dose administered to humans) through the tail vein of mice, and the control group was injected with the same volume of saline. The mice were observed for 7 days including diet, respiration, activity, defecation, skin and pain sensation and other indicators. During the observation period, all the animals were alive and have no abnormal reactions.

7. SUV of translational PET/CT Imaging

Table S4. Data of [^{68}Ga]Ga-P137 and [^{68}Ga]Ga-PSMA617 in patients

Tissues(SUVmax)	Patient 1		Patient 2		Patient 3		SUVmax([^{68}Ga]Ga-P137)/ SUVmax ([^{68}Ga]Ga-PSMA-617)
	[^{68}Ga]Ga-P137	[^{68}Ga]Ga-PSMA-617	[^{68}Ga]Ga-P137	[^{68}Ga]Ga-PSMA-617	[^{68}Ga]Ga-P137	[^{68}Ga]Ga-PSMA-617	
Lacrimal Gland	7.2	8.2	8.4	12.1	5.8	4.3	0.97 ± 0.34
Parotid Gland	11.7	10.6	16.6	16.5	9.6	6.9	1.17 ± 0.20
Submandibular Gland	12.6	11.0	14.5	18.2	13.0	9.5	1.10 ± 0.29
Liver	5.2	4.9	6.3	5.6	5.9	5.9	1.06 ± 0.06
Kidney	27.4	26.8	21.9	26.2	27.4	30.8	0.92 ± 0.10
Spleen	6.7	5.8	11.7	12.5	7.1	6.9	1.04 ± 0.11
Bladder	2.4	11.2	13.2	50.4	2.4	20.1	0.20 ± 0.07
Muscle	0.7	0.8	0.9	0.8	0.7	0.8	0.96 ± 0.14
Cancer lesion							
Primary PCa	9.1	11.1	--	--	12.4	10.8	
Bone metastasis 1	--	--	--	--	6.3	3.9	
Bone metastasis 2	--	--	--	--	6.2	4.8	
Lymph node metastasis1	--	--	12.2	14.5	--	--	0.97 ± 0.32
Lymph node metastasis2	--	--	13.2	19.3	--	--	
Lymph node metastasis3	--	--	28.5	31.0	--	--	
Lymph node metastasis4	--	--	22.6	30.1	--	--	
Lymph node metastasis5	--	--	13.1	19.1	--	--	

Figures

Figure 1

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Figure 2

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Figure 4

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Figure 5

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Supplementary Files

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