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Prostate tumor specific peptide–peptoid hybrid prodrugs

Jiyoun Lee [a,†], Wei Huang [b,†], James M. Broering [b], Annelise E. Barron [b,*], Jiwon Seo [c,*]

[a] Department of Global Medical Science, Sungshin University, Seoul 142-732, Republic of Korea
[b] Department of Bioengineering, Stanford University, Palo Alto, CA 94305, USA
[c] Division of Liberal Arts and Sciences and Department of Chemistry, Gwangju Institute of Science and Technology, 123 Cheomdan gwagiro, Buk-gu, Gwangju 500-712, Republic of Korea

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ABSTRACT

Inspired by naturally occurring host defense peptides, cationic amphipathic peptoids provide a promising scaffold for anti-cancer therapeutics. Herein, we report a library of peptide–peptoid hybrid prodrugs that can be selectively activated by prostate cancer cells. We have identified several compounds demonstrating potent anti-cancer activity with good to moderate selectivity. We believe that these prodrugs can provide a useful design principle for next generation peptide–peptoid hybrid prodrugs.

Antimicrobial peptides (AMPs) have long served as an effective defense for virtually every living organism and are indispensable parts of the innate immunity.[1] Most AMPs are relatively short (10–50 amino acids), highly cationic (+2 to +9), and also contain a significant proportion of hydrophobic residues (over 30%).[1,2] These properties allow AMPs to form amphipathic structures that can interact with the negatively charged outer membrane of microbes and lead to membrane permeation and disruption.[1] Because the membranes of normal eukaryotic cells consist of lipids with no net charge (i.e., phosphatidylcholine), most cationic AMPs are selectively effective against prokaryotic cells.[3] Interestingly, it has been also reported that AMPs exhibit anti-cancer activity possibly due to higher content of negatively charged phosphatidylserine on the outer membrane of rapidly dividing cancer cells.[4–6] This potent and selective cytotoxicity against cancer cells makes AMPs an excellent alternative that can overcome the issues with drug resistance and therapeutic range.[7,8]

Despite the advantages of AMPs over conventional therapeutic agents, AMPs have not yet been used widely in the clinic due to several reasons including rapid proteolytic degradation, potential immunogenicity, and systemic toxicity.[8,9] Various synthetic non-natural analogs of AMPs have been developed to overcome these limitations.[10–12] Among these peptidomimetics, oligo-*N*-substituted glycines (or peptoids) are thought to be a marked candidate because they are highly resistant to proteolysis and indicate lack of immunogenicity while maintaining structural and functional characteristics of peptides.[13–16] These unique features of peptoids come from having a peptide backbone with side chains attached to the amide nitrogen rather than to the α-carbon. Another advantage of peptoids over other peptidomimetics is that peptoids can be readily prepared using the solid-phase submonomer synthesis protocol in a sequence-specific manner.[17]

Recently, we have demonstrated that a library of cationic amphipathic peptoids exhibited a broad spectrum of cytotoxicity against various cancer cell lines including cells with multidrug resistance.[18] Notably, these peptoids effectively inhibited tumor growth in a mouse model of breast cancer suggesting that amphipathic peptoids are a promising alternative for anti-cancer AMPs; however, it was also apparent that the issues with overall selectivity and systemic toxicity should be addressed for further development. Therefore, as a continuing effort to develop amphipathic peptoids for anti-cancer therapy, we have designed peptide–peptoid hybrid prodrugs for the treatment of prostate cancer.

Prostate cancer is one of the most common cancers among men and the sixth leading cause of cancer-related death in males worldwide.[19] Although most prostate cancers can be often treated

* Corresponding authors at present addresses: Department of Bioengineering, Stanford University, W300B James H. Clark Center, 318 Campus Drive, Stanford, CA 94306-5444, USA. Tel.: +1 650 796 4001; fax: +1 650 723 9801 (A.E.B.), Division of Liberal Arts and Sciences and Department of Chemistry, Gwangju Institute of Science and Technology, 123 Cheomdan gwagiro, Buk-gu, Gwangju 500-712, Republic of Korea. Tel.: +82 62 715 3628; fax: +82 62 715 3609 (J.S.).

E-mail addresses: aebarron@stanford.edu (A.E. Barron), jseo@gist.ac.kr (J. Seo).

† These authors contributed equally to this work.

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successfully, patients with advanced and metastatic prostate cancers mainly rely on hormonal therapy, to which patients eventually become unresponsive due to the development of hormone-refractory prostate cancer.[20] Recently, it has been reported that patient-specific vaccines[21] and second and third-generation taxanes[22] appear to extend overall survival of patients suggesting that highly selective cytotoxic agents with less chance of acquiring drug resistance can provide an improved treatment option for hormone-refractory prostate cancer. We believe that anti-cancer peptoids that can be selectively activated by prostate cancer cells perfectly meet these criteria; therefore, we designed our peptide–peptoid hybrid prodrugs (Fig. 1).

To achieve high selectivity, we conjugated the peptides targeting prostate specific antigen (PSA) and prostate specific membrane antigen (PSMA) to parent peptoid (**1**).[16,18] Both PSA and PSMA are overexpressed in prostate cancer and exert catalytic activity. More specifically, PSA is an endopeptidase that is active in the local environment near prostate cancer cells,[23] and PSMA is a carboxypeptidase that cleaves terminal γ-linked glutamic acids.[24] It has been reported that the amino acid sequences of His-Ser-Ser-Lys-Leu-Gln (HSSKLQ),[25] and a non-natural amino acid derivative, 4-hydroxyprolyl-Ser-Ser-cyclohexylglycyl-Gln-Ser-Ser-Pro ($H_{yp}SSC_{hg}QSSP$)[26] can be efficiently hydrolyzed by PSA. Another recent work demonstrated that the crown ether modified peptides with γ-linked glutamic acids can selectively inhibit growth of PSMA over-expressed LNCaP cells.[27] Therefore, we decided to incorporate these specific peptide sequences and amino acids into our parent peptoid (**1**) to generate a series of prodrugs and investigate their anti-cancer activity. As shown in Table 1, we designed PSA-targeted prodrugs (**2**–**3** and **7**–**8**), PSMA-targeted prodrugs (**4**–**6**), and PSA-PSMA dual targeting prodrugs (**9**–**14**). Notably, the pro-moieties of **7** and **8** are attached at the ε-amine of the *N*Lys side chain rather than at the N-terminus of the prodrug sequence. All compounds except **7** and **8** were synthesized on an automated peptide synthesizer according to the peptoid submonomer protocol and standard Fmoc/tBu solid-phase peptide synthesis (SPPS) method.[17] Synthesis of peptide–peptoid hybrids **7** and **8** was carried out manually on a solid-phase resin, and detailed synthetic procedures and HPLC purification conditions are provided in the Supplementary data.

To assess anti-cancer activity of the hybrid prodrugs, we carried out MTS assays of each compound on PSA/PSMA-producing prostate cancer cells (LNCaP) and non PSA/PSMA-producing prostate cancer cells (PC-3) as described in Table 2. We found that our initial PSA-targeting compounds, **2** and **3**, exhibited moderate cytotoxicity and slightly better selectivity against PSA-producing LNCaP cells compared to the parent peptoid (**1**). It was also observed that the HSSKLQ moiety (compound **3**) seemed to be cleaved more efficiently than the non-natural sequence, $H_{yp}SSC_{hg}QSSP$ (compound **2**). On the other hand, the PSMA-targeting compounds (**4**–**6**) showed comparable cytotoxicity with LC_{50} values ranging from 9.5 to 15 μM against LNCaP cells; however, they also exhibited similar degree of cytotoxicity against PC-3 cells, indicating that the γ-glutamate group alone might not be a suitable pro-moiety. Although previously reported work showed that the γ-glutamate groups at the N-termini seemed to be hydrolyzed more efficiently than the same groups at the C-termini,[27] it should be noted that PSMA is an exopeptidase catalyzing the hydrolytic cleavage of glutamates at the C-terminus.[28] Overall, compounds in this group (**2**–**6**) appeared to be less cytotoxic than compound **1** suggesting that the pro-moiety on the N-terminus could not be cleaved effectively possibly due to steric hindrance.

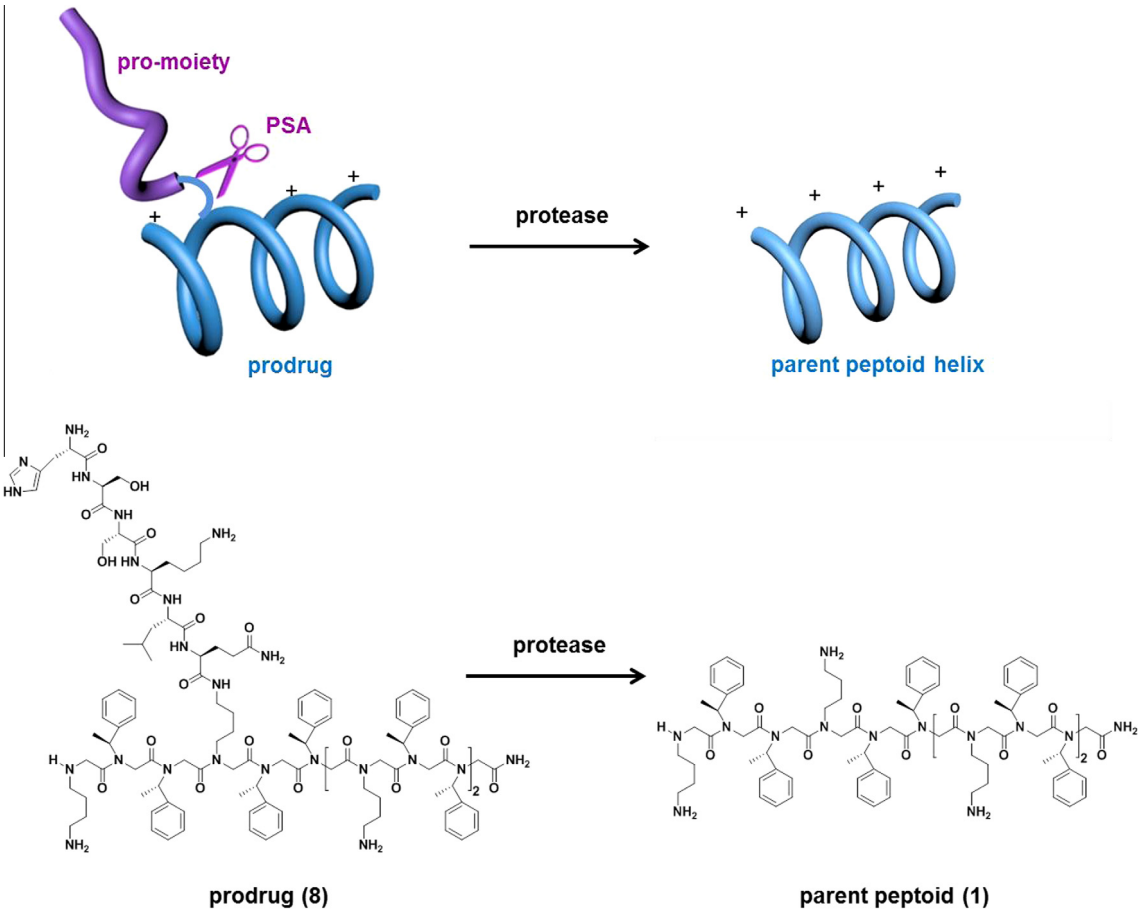

Figure 1. Design strategy of peptide–peptoid hybrid prodrugs.