Published in final edited form as:
J Am Chem Soc. 2010 October 6; 132(39): 13648–13650. doi:10.1021/ja1058982.

Affinity Purification of Multi Functional Polymer Nanoparticles

Yu Hoshino[*], **Walter W. Haberaecker III**, **Takashi Kodama**, **Zhiyang Zeng**, **Yoshio Okahata**, and **Kenneth J. Shea**[*]
Department of Chemistry, University of California Irvine, Irvine, CA 92697 USA, Department of Mechanical Engineering, Stanford University, Stanford, CA 94305 USA, and Department of Biomolecular Engineering, Tokyo Institute of Technology, Yokohama 226-8501, Japan

Abstract

We report that multi functional polymer nanoparticles approximately the size of a large protein can be "purified", on the basis of peptide affinity just as antibodies, using an affinity chromatography strategy. The selection process takes advantage of the thermo-responsiveness of the nanoparticles allowing "catch and release" of the target peptide by adjusting the temperature. Purified particles show much stronger affinity (Kd_{app} ≈ nM) *and* a narrower affinity distribution than the average of particles before purification (Kd_{app} > μM) in room temperature, but can release the peptide just by changing temperature. We anticipate this affinity selection will be general and become an integral step for the preparation of "plastic antibodies" with near homogeneous and tailored affinity for target biomacromolecules.

General procedures for the creation of synthetic materials with biomacromolecular recognition sites are of significant interest as a route to stable, robust and mass-produced substitutes for antibodies.[1–8] Ideally, recognition of complex biological targets, including proteins, peptides and carbohydrates, requires multiple functional groups that contact target molecules by a combination of electrostatic, hydrogen-bonding, van der Waals, and/or hydrophobic interactions. It has been shown that copolymerization of optimized combinations and ratios of functional monomers creates synthetic polymer materials with molecular recognition sites.[1–5] However, in contrast to antibodies whose exact sequence can be determined and cloned, polymerized materials result in heterogeneous structures with a distribution of recognition sites.[1,3,7] This is an intrinsic property of polymers synthesized under kinetic control, in contrast to the synthetic small molecular hosts prepared by multi step reactions[9] or by self-assembly under equilibrating conditions[10]. Here we demonstrate a general procedure to purify synthetic polymer nanoparticles (NPs) with high-affinity binding sites for a target biomacromolecule from a random pool of multi-functional copolymer nanoparticles (MFNPs). These nanoparticles are approximately the size of a large protein and are "purified" on the basis of peptide affinity just as antibodies, using an affinity chromatography strategy.

yhoshino@chem-eng.kyushu-u.ac.jp; kjshea@uci.edu.

Supporting Information Available: Experimental procedures and supporting data are available via the Internet at http://pubs.acs.org.

The concept of affinity purification of NPs was demonstrated with melittin, a 26 amino acid peptide (fig. 1a), as the target molecule. Melittin has six positive charges of which four are localized in a hydrophilic six amino acid sequence on the C-terminus. The remaining twenty amino acids have a high proportion of apolar residues.[11]

For the MFNPs, we chose cross-linked *N*-isopropylacrylamide NPs (~30 nm) incorporating hydrophobic (*N*-t-butylacrylamide (TBAm)) and negatively charged (acrylic acid (AAc)) functional monomers (fig. 1b). We have reported that NPs with this composition interacts with melittin ($K_{d\text{app}}$ = 46 μM) via both electrostatic- and hydrophobi nteractions in PBS (35mM phosphate buffer/0.15 M NaCl, pH 7.3).[5] However, the melittin affinity of the NPs exhibits a significant medium effect–there is only a modest affinity for melittin in low salt containing media such as water. The medium effect may be attributed to hydrophobic interactions between melittin and the NPs that are enhanced by the salting out effect of sodium phosphate and chloride ion.[12]

NPs were synthesized by a free radical copolymerization. To quantify the concentration of the NPs by fluorescence and to monitor the hydration of polymer chains by the solvatochromic shift of λ_{em}, *N*-[2-[[[5-(dimethylamino)-l-naphthalenyl]sulfonyl]-amino]ethyl]-2-methyl-2-propenamide was synthesized and incorporated (1 mol%) to the NPs (supporting information).[13] The concentration of total monomer, cross linker and surfactant (sodium dodecyl sulfate) were optimized to adjust the size of the NPs to approximately 30 nm.[5,8,14] Incorporation of t-butyl (41 mol%) and carboxylic acid (2.3 mol %) group in the MFNPs were quantified by ^{1}H NMR and inverse-gated ^{13}C NMR utilizing ^{13}C-enriched AAc (supporting information). NP size was determined by DLS and AFM (fig. 1c).

The protocol for affinity sorting is shown in fig. 2a. To sort MFNPs on the basis of melittin affinity, we immobilized melittin on avidin agarose beads thru an avidin-biotin interaction (supporting information). NPs are first incubated with melittin-agarose beads for 2 h at 25 °C. Here, 100 mM phosphate buffer was used as the NP adsorption media since interactions between melittin and NPs in water were too weak to isolate sufficient amounts of NPs for study (supporting fig. 1). The supernatant was then separated from the beads and the concentration of NPs remaining in the supernatant was quantified by fluorescence. When NPs (12 μg ml^{-1}) were incubated with different volumes of melittin-immobilized beads, the amount of NPs that were captured by the beads depended on the volume of melittin-beads when the volume of beads was less than ~20 μL mL^{-1}. However, when more than ~20 μL mL^{-1} of beads were incubated, no further capture of NPs were observed–approximately 40 % of the NPs remained in the supernatant (fig. 2b). The interaction between melittin and NPs *before incubation* or the *unbound fraction* remaining in the supernatant *after* incubation was analyzed by 27-MHz QCM in 100 mM phosphate buffer.[5,8,15] The QCM results showed that MFNPs in the *unbound fraction* did not interact with melittin, although, the MFNPs *before incubation* showed a modest interaction with melittin under the same conditions (fig. 2b insert). This indicates the as synthesized MFNPs are comprised of a heterogeneous mixture of particles some of which have melittin affinity under the binding conditions (100 mM phosphate) and others do not.

Melittin immobilized beads that were incubated with NPs (120 μl ml^{-1}) were washed extensively (12 h/cycle) with pure water at 25 °C. During the first few cycles, quantities of NPs were washed from the beads. However, the concentration of NPs diminished with every washing cycle and no NPs were detected after the 8th cycle. QCM revealed that the NPs from this *wash fraction* rebound with melittin in 100 mM phosphate buffer but little interaction was observed in water (fig. 2c insert), indicating NPs that recognize melittin in

100 mM phosphate buffer but not in water were removed from the beads in this washing step (fig. 2c).

In the general protocol for affinity purification of proteins, isolated molecules on the solid affinity support can be released by selective elution induced by either pH and/or salt gradients or by adding an excess of competing ligand.[16] In this study, we capitalized on the temperature-induced phase change of the NIPAm based MFNPs.[2,5,14] Our NPs undergo a thermal phase transition at ~10 °C (supporting information, supporting fig. 2).[14] Above the transition temperature, where they are synthesized, and where affinity (adsorption) studies are carried out, they have a collapsed structure some of which contain melittin affinity sites. Below the transition temperature they are solvent swollen and little affinity to melittin was observed.[5]

When beads washed at 25 °C were incubated at 1 °C in water for 12 h, significant amounts of NPs were released from the melittin-immobilized beads (fig. 2d). In contrast, relatively few NPs were eluted from agarose beads that were not functionalized with melittin (control beads). QCM experiment revealed that the NPs that were released by this *cold elution* were found to strongly interact with melittin at 25 °C in pure water (Kd_{app} = 0.66–2.3 nM, fig. 2d insert). This affinity is comparable to a typical antibody-antigen interaction. In addition, the affinity switching was reversible through 5 cycles of cooling (1 °C) and warming (25 °C). *Cold elution* was observed from melittin-immobilized beads for the first few elution cycles (12 h/cycle). The amount of NPs released after the third elution cycle however was dramatically lower and no NPs were detected after the 6th elution cycle (fig. 2d). This establishes that the affinity for melittin could be dramatically lowered by cooling to 1 °C resulting in their release from the agarose beads. The yield of NPs in the *cold elution step* is several percent, but importantly they showed a significantly stronger affinity for melittin than the NPs *before* affinity sorting (Note-the interaction measured by QCM in water was not observed *before* sorting (fig. 2d insert)). To compare the affinity distribution of NPs in solution *before sorting* and those released by *cold elution*, each batch of NPs (240 ng ml^{-1}) were incubated with melittin immobilized beads in water at 25 °C overnight. Although only a part of the NPs were captured from the NPs *before sorting*, all of the NPs in the *cold elution* were re-captured by melittin-immobilized beads (supporting fig. 3). This result indicates that the affinity distribution of the NPs released by *cold elution* is narrower than the NPs *before sorting*.

From these results, we conclude that synthetic polymer nanoparticles with high-affinity for the peptide melittin can be “purified” from a random pool of multi-functional copolymer nanoparticles by an affinity chromatography strategy. Each fraction isolated during the affinity sorting process shows a different affinity for the target peptide. The “selected” NPs have a much stronger and narrower affinity distribution than the materials before purification. We anticipate this affinity purification is applicable for most nano-size materials for molecular-recognition including molecularly imprinted NPs[8] and functionalozed inorganic NPs[17], and will become an integral step for the preparation of “plastic antibodies” with near homogeneous and tailor made affinity for target molecules.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

We thank Dr. T. Ozeki at Initium, Inc. for the QCM measurement, D. Gatanaga and Dr. S. Takahashi for the fluorescent measurements and financial support from the National Institutes of Health (GM080506).

References

1. Jozefowicz M, Jozefonvicz J. Biomaterials. 1997; 18:1633–44. [PubMed: 9613811]
2. Oya T, Enoki T, Grosberg AY, Masamune S, Sakiyama T, Takeoka Y, Tanaka K, Wang G, Yilmaz Y, Feld MS, Dasari R, Tanaka T. Science. 1999; 286:1543–1545. [PubMed: 10567256]
3. Peppas NA, Huang Y. Pharm Res. 2002; 19:578–87. [PubMed: 12069158]
4. Koch SJ, Renner C, Xie X, Schrader T. Angew Chem, Int Ed Engl. 2006; 118:6500–6503.
5. Hoshino Y, Urakami T, Kodama T, Koide H, Oku N, Okahata Y, Shea KJ. Small. 2009; 5:1562–1568. [PubMed: 19296557]
6. Vlatakis G, Andersson LI, Muller R, Mosbach K. Nature. 1993; 361:645–647. [PubMed: 8437624]
7. (a) Wulff G. Angew Chem, Int Ed Engl. 1995; 34:1812–1832. (b) Haupt K, Mosbach K. Chem Rev. 2000; 100:2495–2504. [PubMed: 11749293] (c) Sajonz P, Kele M, Zhong G, Sellergren B, Guiochon G. J Chromatogr A. 1998; 810:1–17. (d) Umpleby RJ, Baxter SC, Chen Y, Shah RN, Shimizu KD. Anal Chem. 2001; 73:4584–4591. [PubMed: 11605834]
8. (a) Hoshino Y, Kodama T, Okahata Y, Shea KJ. J Am Chem Soc. 2008; 130:15242–3. [PubMed: 18942788] (b) Hoshino Y, Koide H, Urakami T, Kanazawa H, Kodama T, Oku N, Shea KJ. J Am Chem Soc. 2010; 132:6644–6645. [PubMed: 20420394]
9. (a) Dougherty DA, Stauffer DA. Science. 1990; 250:1558–1560. [PubMed: 2274786] (b) Still WC. Acc Chem Res. 1996; 29:155–163. (c) Zimmerman SC, Wendland MS, Rakow NA, Zharov I, Suslick KS. Nature. 2002; 418:399–403. [PubMed: 12140553]
10. (a) Huc I, Lehn JM. Proc Natl Acad Sci USA. 1997; 94:2106–10. [PubMed: 9122156] (b) Otto S, Furlan RLE, Sanders JKM. Science. 2002; 297:590–593. [PubMed: 12142534] (c) Corbett PT, Leclaire J, Vial L, West KR, Wietor JL, Sanders JKM, Otto S. Chem Rev. 2006; 106:3652–3711. [PubMed: 16967917]
11. Habermann E. Science. 1972; 177:314–322. [PubMed: 4113805]
12. Melander W, Horváth C. Arch Biochem Biophys. 1977; 183:200–215. [PubMed: 907351]
13. Shea KJ, Stoddard GJ, Shavelle DM, Wakui F, Choate RM. Macromolecules. 1990; 23:4497–4507.
14. (a) Debord JD, Lyon LA. Langmuir. 2003; 19:7662–7664. (b) Ogawa K, Nakayama A, Kokufuta E. Langmuir. 2003; 19:3178–3184.
15. Hoshino Y, Kawasaki T, Okahata Y. Biomacromol. 2006; 7:682–5.
16. Cuatrecasas P. Annu Rev Biochem. 1971; 40:259–78. [PubMed: 4399260]
17. (a) Verma A, Nakade H, Simard JM, Rotello VM. J Am Chem Soc. 2004; 126:10806–10807. [PubMed: 15339141] (b) De, Mrinmov; You, C-C.; Srivastava, S.; Rotello, VM. J Am Chem Soc. 2007; 129:10747–10753. [PubMed: 17672456]

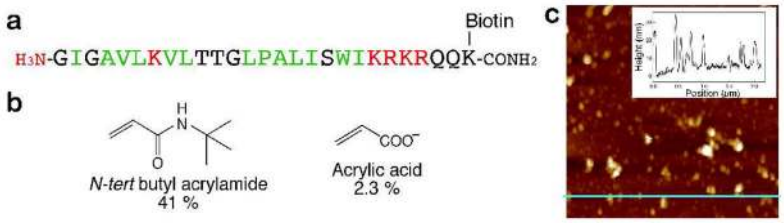

Figure 1.

a, Amino acid sequence of melittin. Hydrophobic and positive charged residues are printed in green and red respectively. **b**, The chemical structures of functional monomers used for NP synthesis. **c**, Solution phase AFM images of NPs. A height profile of cross-section (light blue line) is shown in insert.

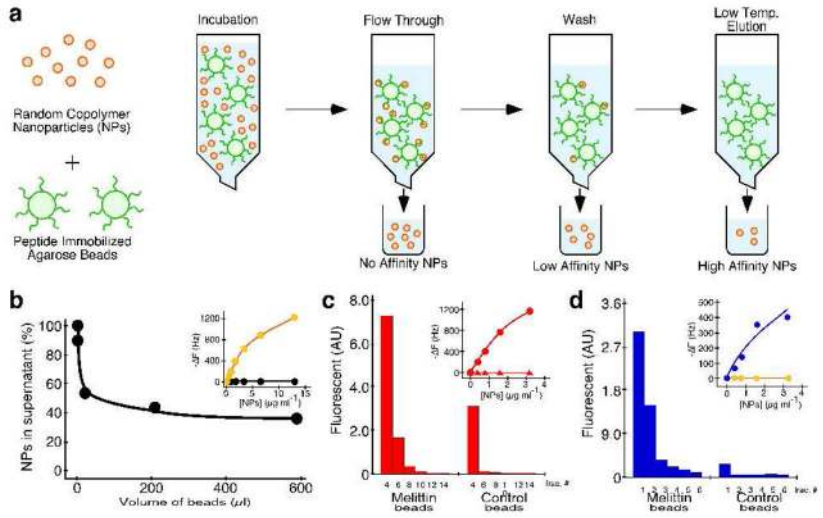

Figure 2.

a, Protocol for affinity sorting. Randomly copolymerized NPs are incubated with melittin immobilized agarose beads in 100 mM phosphate buffer (pH7.4) at 25 °C. Ratio of NPs remaining in solution after incubation with different volumes of melittin immobilized beads is plotted in (**b**). Interaction (QCM) between melittin and NPs before incubation (yellow) and remaining after incubation (gray) is shown in (**b**) insert. NPs on the beads were first washed with water at 25 °C then eluted with cold water (1 °C). Each cycle (12 hour incubation) was repeated until no further elution of NPs was observed. Fluorescent intensity of NPs in each fraction from washing (red) and cold elution (blue) cycles is plotted in (**c**) and (**d**) respectively. Interaction between melittin and wash fraction in 100 mM phosphate buffer (red circles) and in water (red triangles) at 25 °C are shown in (**c**) insert. Interaction between melittin and NPs before incubation (yellow) and cold elution (blue) in water at 25 °C are shown in (**d**) insert.