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Controlled Synthesis of Phosphorylcholine Derivatives of Poly(serine) and Poly(homoserine)

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Supporting Information

ABSTRACT: We report methods for the synthesis of polypeptides that are fully functionalized with desirable phosphorylcholine, **PC**, groups. Because of the inherent challenges in the direct incorporation of the **PC** group into α-amino acid *N*-carboxyanhydride (NCA) monomers, we developed a synthetic approach that combined functional NCA polymerization with efficient postpolymerization modification. While poly(L-phosphorylcholine serine) was found to be unstable upon synthesis, we successfully prepared poly(L-phosphorylcholine homoserine) with controlled chain lengths and found these to be water-soluble with disordered chain conformations.

Phospholipids are ubiquitous in biology as major components of cell membranes, and many contain phosphatidylcholine. Because of the biomimetic and biocompatible properties of the phosphorylcholine, **PC**, functional group, it has been incorporated into a wide variety of polymeric materials for use in applications including drug delivery,[1−3] imaging,[4−6] and preparing surfaces that resist protein adsorption and cell adhesion.[7−9] Although they possess promising properties, most **PC** polymers are nondegradable, which limits the scope of their use especially for applications *in vivo*.[10] Recently, there has been much interest in the preparation of functional polypeptide materials that may be useful as degradable and more biologically relevant alternatives to nondegradable functionalized polymers.[11] Hence, we sought methods to incorporate **PC** functionality into polypeptides to prepare zwitterionic, potentially degradable polymers bearing biocompatible groups that may resist protein and cell adhesion. We describe our results on the synthesis of **PC** derivatives of poly(serine), **PC-S**, and poly(homoserine), **PC-S^{H}**, via a combination of functional NCA monomer polymerization and postpolymerization amination (Figure 1).

Most studies on **PC** polymers have focused on poly(2-methacryloyloxyethyl phosphorylcholine), **PMPC**, which has excellent nonfouling properties, yet also a nondegradable polymer backbone.[12,13] Degradable **PC** polyesters have been prepared but required the postpolymerization addition of the **PC** groups using long tethers.[14] Polypeptides with **PC** functionality have only been prepared as derivatives of poly(lysine) and poly(glutamate), where **PC** groups were covalently attached to side-chain functional groups postpolymerization.[15] In these materials, long spacers were also needed between the **PC** groups and the polypeptide backbone, and the highest degree of functionalization attained was 80%. Otherwise, phosphate[16] and phosphonate[17,18] containing polypeptides, mainly based on poly(phosphoserine) or its analogues, are the only other phosphorus containing polypeptides that have been prepared. These polypeptides were prepared from the corresponding functionalized α-amino acid-*N*-carboxyanhydride (NCA) monomers and could be obtained with controlled lengths and low polydispersities in some cases.

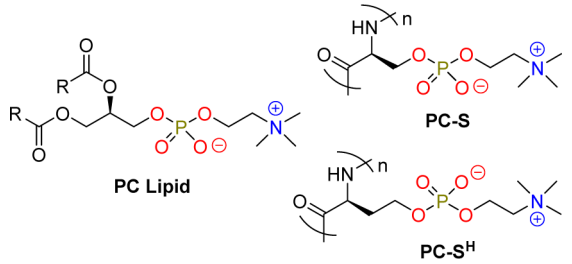

Figure 1. Structures of phosphorylcholine containing lipids and polypeptides. PC = phosphorylcholine; R = lipid tails; S = serine; S^{H} = homoserine.

To enable an efficient synthesis of fully functionalized **PC** polypeptides, especially those with structures similar to the natural phosphoserine, we undertook an approach that combined the preparation and polymerization of a functionalized NCA monomer with an efficient postpolymerization modification.[19] The main challenge associated with incorporating **PC** groups into polypeptides is that this functionality is not easily protected, and there is no precedent for polymerization of NCA monomers containing charged quaternary ammonium groups. Hence, our strategy necessitated preparation of a suitably protected phosphoserine NCA, which after polymerization could then be directly converted to a **PC** serine polypeptide by reaction of bromoethyl groups with trimethylamine (eq 1). Success of the approach required identification of an appropriate phosphate protecting group that could be removed without loss of the bromoethyl functionality.

Our initial studies revealed that alkyl protecting groups for phosphoserine NCAs, such as methyl, ethyl, and isopropyl, gave polymers with poor solubility in common solvents. Attempts to use other groups such as 2-cholorophenyl[20] and 2-trimethylsilylethyl[21] gave NCA monomers that were unstable and challenging to purify. Following these initial setbacks, we developed a more modular approach toward quickly testing

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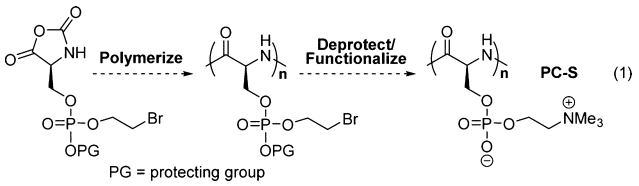
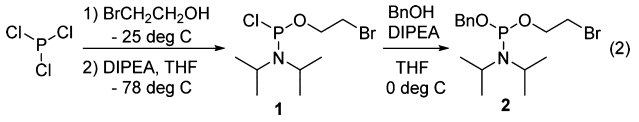
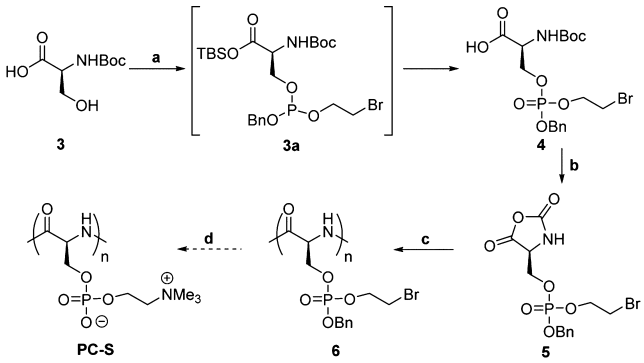


suitable protecting groups. Building on methods developed for DNA and nucleotide synthesis[22,23] we prepared cholorophosphoramidite reagent **1**, which could be stored for long periods at −20 °C and also functionalized with a variety of different protecting groups (eq 2). We found that the benzyl protecting group was well suited for subsequent steps, and so phosphoramidite reagent **2** was synthesized for use in NCA synthesis (eq 2).



NCA monomer synthesis began with commercially available Boc-L-serine **3**, where the α-carboxylate was protected in situ using *tert*-butyldimethylsilyl chloride, TBSCl, followed by phosphitylation with reagent **2**. The resulting phosphite **3a** was then oxidized to the phosphate with *tert*-butyl hydroperoxide, *t*BuOOH, and the TBS protecting group was removed in aqueous workup, yielding NCA precursor **4** in nearly quantitative yield over this three-step, one-pot reaction. NCA synthesis was achieved in reasonable yield using phosgene, and the product was purified using anhydrous silica chromatography in a glovebox (Scheme 1).[24] Polymerizations of NCA **5** using $Co(PMe_3)_4$ in

Scheme 1. Attempted Synthesis of Poly(L-phosphorylcholine serine), PC-S[a]



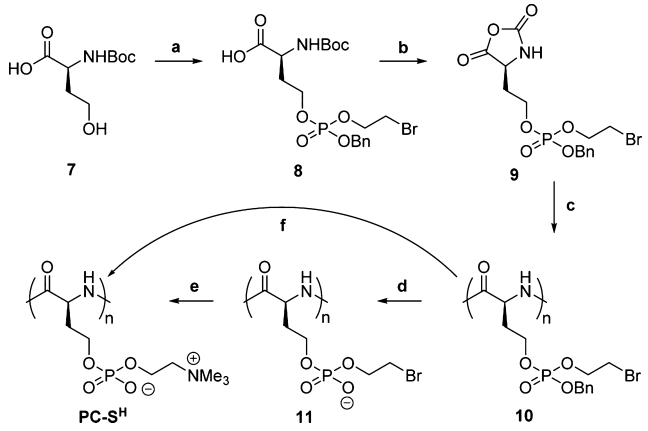
[a](a) (i) TBSCl, THF, *N*-methylmorpholine; (ii) **2**, tetrazole and MeCN; (iii) tBuOOH (95% yield). (b) $COCl_2$, *N*-methylmorpholine, THF, 40 °C (63% yield). (c) $Co(PMe_3)_4$, THF, see SI for yields. (d) Multiple attempts, see text.

THF proceeded readily at ambient temperature to give corresponding soluble homopolypeptides **6** with complete monomer conversion and no reactions at the side-chain phosphate or alkyl bromide groups (Scheme 1).[25] It is worth noting that the polymerization of **5** may not be feasible using amine-initiated NCA polymerization methods due to possible S_N2 side reactions at the primary alkyl bromide groups.

We next attempted the transformation of **6** to the desired product poly(L-phosphorylcholine serine), **PC-S**. We reasoned that due to the known short half-lives of phosphotriesters in aqueous solutions,[26] we would have been able to remove the labile benzyl group and aminate the 2-bromoethyl group in one step. Thus, **6** was subjected to 20% aqueous trimethylamine, which caused the water-insoluble polymer **6** to form a clear solution within 10 min. However, no polymer was isolated following dialysis. A stepwise debenzylation of **6** followed by attempted amination with trimethylamine yielded similar results. It was apparent that chain cleavage reactions were occurring under these basic conditions. A possible mechanism for this is via β-elimination of the phosphate group, which is known to occur in phosphoserine derivatives.[27−29] We have also previously observed similar behavior in phosphonate-containing serine analogues.[18] In polymer **6**, β-elimination of phosphates would yield dehydroalanine residues. These groups would likely rehydrate to give DL-serine repeats, which are known to decompose under both basic and acidic conditions (see eq S1).[30] To eliminate this problem, we recognized that β-elimination and subsequent polymer degradation can be avoided by the homologation of serine to homoserine. β-Elimination on serine derivatives yields dehydroalanine, which contains a stabilized α,β-unsaturated olefin, while a homoserine derivative would not yield such a stabilized product.

Consequently, a homoserine polypeptide analogue of **6** was synthesized using a similar procedure, starting with the commercially available Boc-L-homoserine **7**, which was elaborated to **8** using the aforementioned three-step one-pot reaction. NCA **9** was synthesized using Ghosez's reagent[31] and was purified using anhydrous silica chromatography (Scheme 2).[24]

Scheme 2. Synthesis of Poly(L-phosphorylcholine homoserine), PC-S^H[a]



[a] (a) (i) TBSCl, THF, *N*-methylmorpholine; (ii) **2**, PPTS and MeCN; (iii) *t*BuOOH (85% yield). (b) Ghosez reagent, THF (80% yield). (c) $Co(PMe_3)_4$, THF, see Table 1 for yields. (d) TFA/DCM 1:1 (95% yield). (e) 20% aq. NMe_3 (95% yield). (f) 20% aq. NMe_3 (90% yield).

Polymerizations of NCA **9** using $Co(PMe_3)_4$ in THF proceeded readily at ambient temperature to give the corresponding soluble homopolypeptides **10** with complete monomer conversions with no detectable side reactions.[25] Residual cobalt salts were readily removed by washing the polypeptides with water. In order to gauge if chain lengths could be controlled, **9** was polymerized to completion at different monomer to initiator, M/I, ratios, and active chains were then end-capped with isocyanate terminated polyethylene glycol monomethyl ether (PEG-NCO, M_n = 1000 Da).[32] The polymers were purified and analyzed by ^{1}H NMR to obtain the number-average molecular weights, which increased

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linearly with M/I stoichiometry (Table 1). Chain length distributions of samples of **10** were obtained by GPC/RI analysis, and polydispersity indices were found to range from 1.14 to 1.24, indicating that well-defined polypeptides were formed (Table 1, Figure 2).

Table 1. Synthesis of Polymer 10 at Different Monomer to Initiator (M/I) Ratios

M/I[a]	M_n[b]	M_w/M_n[c]	DP[d]	yield (%)[e]
10:1	12 800	1.19	34	89
20:1	28 300	1.24	75	91
30:1	35 900	1.21	87	90
40:1	49 100	1.14	130	95

[a]Equivalents of monomer **9** per $Co(PMe_3)_4$. [b]Molecular weight determined for PEG end-capped samples using ^1H NMR. [c]Polydispersity index determined by GPC/RI analysis. [d]DP = degree of polymerization. [e]Total isolated yield of purified polypeptide.

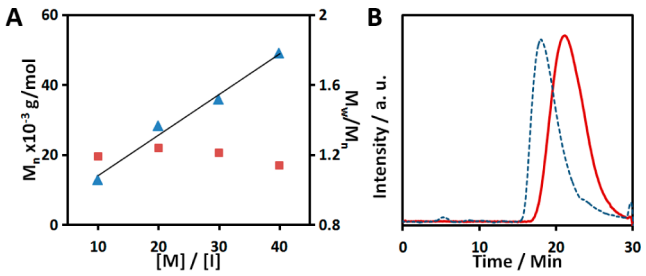

Figure 2. Chain length control and polydispersity of polymer **10**. (A) Molecular weight (M_n, ■) and polydispersity index (M_w/M_n, ▲) of **10** as a function of monomer to initiator ([M]/[I]) ratio using $Co(PMe_3)_4$ in THF at ambient temperature. (B) GPC chromatogram (RI intensity in arbitrary units (a.u.) versus elution time) of polymer **10** samples from Table 1 (20:1, solid red, and 40:1, dotted blue).

Modification of polymer **10** to give poly(L-phosphorylcholine homoserine), **PC-S^H**, was carried out by the removal of the benzyl protecting group to yield **11**, followed by amination using aqueous trimethylamine. The modification can also be accomplished directly by exposing **10** to aqueous trimethylamine. Both methods work well and provide fully functionalized **PC-S^H** in excellent yield and high purity (Scheme 2). Samples of **PC-S^H** were found to be stable in aqueous media for prolonged periods (ca. 1 month) with no signs of degradation.

The chain conformation of **PC-S^H** was examined in aqueous media using circular dichroism (CD) spectroscopy. **PC-S^H** gave CD spectra consistent with a disordered chain conformation over a broad pH range of 3 to 11 (Figure 3). This behavior is expected due to the permanent charges of the PC groups, which disrupt the formation of ordered chain conformations.[33] Similar to other **PC** functionalized polymers, **PC-S^H** was also found to display minimal toxicity to cells *in vitro* (see Figure S1).

The **PC-S^H** polymers reported here are notable in that they are the first polypeptides containing **PC** functionality at every residue. The strategy to prepare these polymers also allows for control over **PC-S^H** chain length and incorporation of these residues into block copolymers, such as with PEG as shown here. Upon initial examination, these polypeptides appear to have properties characteristic of other **PC** polymers and may prove to be useful materials for biomedical research due to the potential biodegradability of their polypeptide backbone.

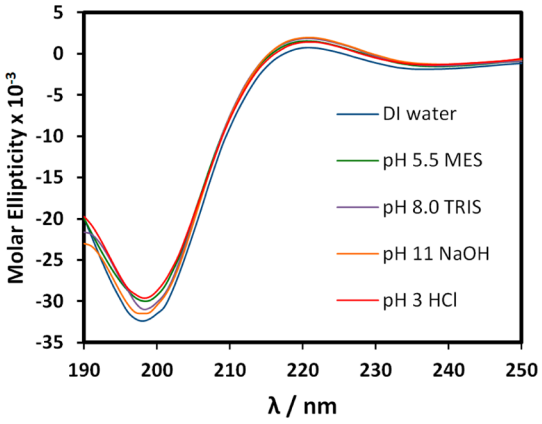

Figure 3. Circular dichroism spectra of **PC-S^H** in different aqueous media (DP = 34, 0.1 mg/mL) at 20 °C.

■ ASSOCIATED CONTENT

Supporting Information

Experimental procedures and data for all new compounds, as well as polymerization data, M_n calculation data, and cell viability data. This material is available free of charge via the Internet at http://pubs.acs.org.

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Author Contributions

The manuscript was written through contributions of all authors.

Notes

The authors declare no competing financial interest.

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