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Peptide–oligonucleotide conjugates as nanoscale building blocks for assembly of an artificial three-helix protein mimic

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Peptide-based structures can be designed to yield artificial proteins with specific folding patterns and functions. Template-based assembly of peptide units is one design option, but the use of two orthogonal self-assembly principles, oligonucleotide triple helix and a coiled coil protein domain formation have never been realized for de novo protein design. Here, we show the applicability of peptide–oligonucleotide conjugates for self-assembly of higher-ordered protein-like structures. The resulting nano-assemblies were characterized by ultraviolet-melting, gel electrophoresis, circular dichroism (CD) spectroscopy, small-angle X-ray scattering and transmission electron microscopy. These studies revealed the formation of the desired triple helix and coiled coil domains at low concentrations, while a dimer of trimers was dominating at high concentration. CD spectroscopy showed an extraordinarily high degree of α-helicity for the peptide moieties in the assemblies. The results validate the use of orthogonal self-assembly principles as a paradigm for de novo protein design.
Designed peptide-based structures have been shown to yield artificial proteins and even in a few cases nanoscale objects. Simultaneously, oligonucleotides (ONs) have been intensively used for nanotechnology, including so-called DNA origami, to create structurally advanced objects such as DNA-based nanoboxes. In contrast, formation of nanoscale objects and artificial proteins from peptide-ON conjugates (POCs) as building blocks with combined involvement of two separate self-assembly principles have, to our knowledge, not yet been realized. Protein de novo design involves rational design of peptide or protein molecules to fold into a target protein or protein-like structure, rather than the use or re-design of a naturally occurring sequence. Protein de novo design offers a test of our understanding of the factors controlling protein structure, folding and stability. The approach also offers the prospect of access to tailor-made proteins. One way to overcome the complexity of protein folding is the concept of template-assembled synthetic proteins (TASPs). Several groups have explored this approach with a diverse set of templates, and we have reported the first low-resolution structure of a TASP in the form of a carboprotein, using small-angle X-ray scattering (SAXS). Well-defined DNA secondary structures such as double helices, triple helices, multi-way junctions and quadruplexes are potential scaffolds in designs of TASPs, requiring POCs as building blocks. Different methods have previously been applied to couple peptides or proteins with ONs, including azide-alkyne cycloaddition reactions due to their remarkable compatibility with diverse functional groups and their high second-order rate constant under mild conditions.

However, to the best of our knowledge, only three examples have been reported on peptide and protein assembly driven by the formation of DNA secondary structures. In one report it was demonstrated that quadruplex formation could orient two very short peptides to form an adjacent two-loop protein-like surface, in another that three- and four-way DNA junctions positioned one recombinant eADF4(C16) element at each terminal, and in a more recent report that two model substrates (a maltose-binding protein and an antibody fragment against urokinase plasminogen activator receptor) positioned on DNA junctions imitated the geometry of an antibody. Previously, POCs have thus not been explored in de novo protein design using two orthogonal self-assembly principles.

For the present proof-of-concept study we relied on a sequence derived from CoilVΛd which was N-terminally extended with an azidohexanoyl-Tyr linker. The α-helical coiled coil is a ubiquitous protein motif that exists in 5–10% of all protein sequences. One of the main characteristics of a coiled coil is the simplicity of its sequence, as it consists of a motif that repeats itself every seven residues. In coiled coils, two or more helices wrap around each other in a left- or right-handed helical twist conformation. These helices can adopt different topologies, as they can assemble in parallel or antiparallel orientation. The solution structure analysis of CoilVΛd also revealed a cooperative monomer–dimer–trimer equilibrium, with the dimer state being an intermediate. Later the crystal structure of CoilVΛd revealed a parallel triple-helical structure.

Herein, we report an efficient and high-yielding preparation of POCs by copper-free alkyne-azole cycloaddition reactions, and we show that ON triple helix-formation can be used to...
organize peptide strands leading to the formation of a highly stable three-helix bundle protein mimic that dimerizes at higher concentrations. Locked nucleic acid (LNA) was central to our design.

**Results**

**Synthesis of POCs.** A convenient and efficient method using copper-free ring-strain promoted azide-alkyne coupling reactions was developed for synthesis of POCs (Fig. 1a). Among strained cyclooctynes41,42, bicyclo[6.1.0]nonyne (BCN) was chosen due to its high second-order rate constant and commercial availability as a phosphoramidite monomer ready for use on an automated DNA synthesizer (Fig. 1b)43,44. In this way the ON building blocks ON1-BCN, ON2-BCN and ON3-BCN were obtained. The azido-labelled peptide was synthesized by automated Fmoc chemistry and N-terminal attachment of a 6-azido hexanoyl group. Efficient and high-yielding preparation of POCs containing long peptide fragments (≥30-mers) or proteins is challenging and only very few successful examples have been published via chemical synthesis35,36,45 but this method furnished the desired conjugates POC1, POC2 and POC3 in satisfactory yields for milligram-scale preparation (further details are included in Supplementary Discussion, Supplementary Methods and Supplementary Figs 1–6).

**Ultraviolet-melting studies and gel electrophoresis analysis.** As a first step in studying the applicability of nucleic acid self-assembly towards organizing peptide bundles (Fig. 1c), the stability of duplexes and triple helices involving one or more POC(s) was evaluated (see also details in Supplementary Methods), with their ON-based counterparts as references (Table 1a). One aspect was to study if the helical structures were stabilized by a synergistic effect involving both the ON and the peptide moieties. A wavelength of 275 nm was used for ultraviolet thermal denaturation (‘melting’) studies where the ultraviolet absorption difference between the triple helix and the underlying duplex is maximal (Supplementary Fig. 7). An ultraviolet-scan showed that the peptide unit did not display significant absorption at this wavelength (Supplementary Fig. 8). For interpretation of these studies it is assumed that any higher-order structures possibly formed (see sections below on gel electrophoretic, SAXS and TEM analysis) have no significant effect on annealing or denaturation of duplexes or triple helices.

In the case of duplex systems (Table 1b), the POC2 + POC3 assembly (Table 1b, entry 4) showed substantially higher thermal stability than the ON2 + ON3 duplex (Table 1b, entry 1), which we attribute to an additional interaction between the peptide moieties acting cooperatively with the Watson–Crick interactions of the ON units (Table 1b, entry 4). The melting curve of the POC2 + POC3 duplex is well superimposed on the corresponding annealing curve (Supplementary Fig. 9), indicating that the peptide modification does not perturb the thermal reversibility of the duplex structure. Importantly, no stabilization was seen for assemblies containing only one peptide unit (Table 1b, entries 2 and 3), strongly supporting that interactions between the peptide units play an indispensable role in stabilizing the POC2 + POC3 structure.

Eight triple-helical complexes were formed using ON1 and POC1 as triple-helix-forming ON (TFO) designed to bind in the major groove of the four duplexes (Table 1b, entries 5–12). A significant increase in melting temperature was observed for the POC1 + POC2 + POC3 triple helix (Table 1b, entry 6) when compared with the corresponding ON1 + ON2 + ON3 triple helix (Table 1b, entry 5). We ascribe this increased stability to the formation of a three-helix parallel peptide bundle, which for the non-conjugated peptides in solution was reported as the predominant structure37,46. Accordingly, the annealing curve for POC1 + POC2 + POC3 gave a clear triple-helix annealing transition, whereas that transition was not detected for the ON1 + ON2 + ON3 triple helix (Supplementary Fig. 10). As expected, there was no or only little improvement of triple-helix stability when ON1 was bound to the three duplexes containing one or two peptide units (Table 1b, entries 7–9, Supplementary Fig. 11). The remaining assemblies displayed in Table 1b (entries 10–12) involve POC1, where increased triple-helix stability was also observed when only one strand of the duplex contained a peptide moiety (Table 1b, entries 10 and 11, Supplementary Fig. 12). This observation again strongly indicates cooperative effects between nucleic acid hybridization and peptide assembly. This was further evidenced by the lack of triple-helix annealing transitions for the assemblies with only one peptide unit (Table 1b, entries 7, 8 and 12) or with the two peptide units on the two duplex-forming strands (Table 1b, entry 9).

For POC1 + POC2 + ON3 and POC1 + ON2 + POC3 where the triple-helix transitions were overlapping with duplex transitions (Table 1b, entries 10 and 11), the experiments were repeated at pH 7.5. The stability of parallel nucleic acid triple helix is pH dependent, and in near physiological conditions the triple helices become less stable when the pH increases, mainly due to de-protonation of N3 of cytosine nucleobases47. Under these conditions, both triple helices exhibited distinctive triple-helix melting and annealing transitions, whereas the transition temperatures for the underlying duplexes were unchanged (Supplementary Fig. 13).

Non-denaturing polyacrylamide gel electrophoresis (see Supplementary Methods for details) was used to study the assemblies discussed above (Table 1). Relatively low-voltage and low-temperature (4 °C) conditions minimized the possible dissociation of any triple helix during electrophoresis.

The reference ON2 + ON3 assembly (Fig. 2, lane 1) appeared as a single band, consistent with the length of the duplex (22-mers). The ON1 + ON2 + ON3 assembly (Fig. 2, lane 3) appeared as one dominant band (triple helix), and a faint band corresponding to the ON2 + ON3 duplex as a result of TFO dissociation (for room temperature conditions see Supplementary Fig. 14). When the pH was increased to 8.5 (Supplementary Figs 15 and 16) only the lower band was observed, consistent with the melting studies where no triple-helix transition was observed at pH 7.5 (Supplementary Fig. 13). The POC1 + POC2 + POC3 assembly (Fig. 2, lane 4) appeared as a dominating band with a far slower mobility than for the corresponding ON-based triple-helix control, confirming an increase in molecular size and mass-to-charge ratio due to the peptide moieties. In addition, a faint band moving close to the 150-mer DNA mark was observed which could be explained by dimerization (or multimerization) of the POC1 + POC2 + POC3 triple helix, possibly induced by additional intermolecular interactions. Similar behaviour was observed at three different conditions (pH 7.0, room temperature in Supplementary Fig. 14; pH 8.5, 4 °C in Supplementary Fig. 15; and pH 8.5, room temperature in Supplementary Fig. 16), demonstrating the existence of POC1 + POC2 + POC3 as a triple helix even at pH 8.5 at room temperature (Supplementary Fig. 16, lane 4) and the remarkable peptide-induced stabilization of the otherwise rather unstable ON triple helix. In contrary to the POC1 + POC2 + POC3 assembly, the POC2 + POC3 as well as other bimolecular assemblies appeared as several bands with a lower mobility than the band for the POC1 + POC2 + POC3 triple helix (Fig. 2, lanes 2, 5 and 6) probably reflecting the formation of various multimeric higher-order structures induced by a drive towards formation of three-stranded peptide domains.

**Circular dichroism spectroscopy.** Figure 3 shows the circular dichroism (CD) spectra of POC1 + POC2 + POC3, azidopeptide,
ON1 + ON2 + ON3 and a sample containing azidopeptide and triple-helix ON1 + ON2 + ON3 at 20 °C (see also Supplementary Methods for details). As expected, the far-ultraviolet CD spectrum of azidopeptide exhibited an intense α-helix signal with negative peaks at 222 and 208 nm, respectively. ON1 + ON2 + ON3 showed a wide positive signal between 305 and 251 nm with a maximum around 284 nm and a shoulder around 260 nm, a wide negative signal between 251 and 206 nm with a shoulder around 240 nm and a maximum around 211 nm, which corresponds to the spectrum of a hybridized B-form DNA. Similarly, the spectral features in the high-wavelength region also indicated the formation of an ON triple helix (Supplementary Fig. 18).

In Fig. 3, the higher wavelengths of the spectrum of POC1 + POC2 + POC3 were characterized by the contribution of the triple-helix ON signals with a wide positive feature between 305 and 251 nm with a maximum around 284 nm. At lower temperatures, the melting properties of the POC-including and ON-reference duplexes (entries 1–4) and triple helixes (entries 5–12) at pH 7.0 measured as an average of three independent melting temperature determinations shown with the corresponding standard deviations. For entries 5–12, the values in brackets are Tm and Ta values measured for the corresponding underlying duplexes. The experiments were recorded at 275 nm in 5.8 mM NaH2PO4/Na2HPO4 buffer (pH 7.0) containing 100 mM NaCl and 0.10 mM EDTA. The concentration of the individual duplex components was 1.0 μM, while the TFO component was used in 1.5 μM concentration. The peptide moiety is marked in green, the TFO moiety in blue and the DNA duplex moiety in red.
values at 222 nm around a plateau was reached at magnitude in the concentration range tested. For the azidopeptide however, the latter exhibited a markedly increased CD signal degree of significantly more intense POC1 between 305 and 251 nm were practically identical to those of the ultraviolet region the positive signals observed for the ON samples where the peptide transitions dominate (Fig. 3). In the near-ultraviolet region the positive signals observed for the ON samples between 305 and 251 nm were practically identical to those of the POC1 + POC2 + POC3 sample. The latter, however, exhibited a significantly more intense α-helix signal, which indicated a higher degree of α-helicity. The \( \theta_{222 \text{ nm}} / \theta_{208 \text{ nm}} \) ratios, assumed to be \( \geq 1 \) for coiled coil peptides, were calculated\(^{19,50} \). Azidopeptide and POCI + POC2 + POC3 (after subtracting the spectrum of ON1 + ON2 + ON3 to remove the contribution of the ON part) showed \( \theta_{222 \text{ nm}} / \theta_{208 \text{ nm}} \) ratios equal to 1.03 and 1.05, respectively. These values are consistent with the existence of stable α-helical coiled coils in solution and POC1 + POC2 + POC3 having a markedly increased helical content (see discussion below).

The concentration dependence of the helical content of POC1 + POC2 + POC3 and azidopeptide were tested by CD spectroscopy (Supplementary Discussion). Compared with the dilute samples shown in Fig. 3, a further change in the mean residue ellipticity was observed when the concentration was increased, both for azidopeptide and POC1 + POC2 + POC3. However, the latter exhibited a markedly increased CD signal magnitude in the concentration range tested. For the azidopeptide a plateau was reached at \( \sim 15 \mu\text{M} \) with mean residue ellipticity values at 222 nm around \(-31,000 \text{deg cm}^{-2} \text{dmol}^{-1} \), whereas further decrease to values below \(-50,000 \text{deg cm}^{-2} \text{dmol}^{-1} \) was observed for POC1 + POC2 + POC3 (Supplementary Fig. 20 and Supplementary Table 1). These observations indicate that the interactions between the ON moieties of POC1 + POC2 + POC3 induced a singularly higher degree of coiled coil in comparison with the unconjugated peptide. The observed CD signal is noteworthy as negative ellipticity values of such a magnitude to the best of our knowledge have never been reported in a purely aqueous solvent at ambient temperature. To evaluate the contribution of the ON region of POC1 + POC2 + POC3 to the ellipticity at 222 nm, we measured samples of unconjugated ON1 + ON2 + ON3 at the same concentrations. In correspondence with the spectra shown in Fig. 3, the signal was in every case \( \sim 10\% \) of that of POC1 + POC2 + POC3 (Supplementary Table 1). CD temperature denaturation studies provided results in agreement with the ultraviolet-melting studies (Supplementary Discussion and Supplementary Figs 21–24).

Small-angle X-ray scattering. SAXS analysis was used to provide information on overall structure and oligomeric state of the
self-assembled complexes (Table 2a). Performing an indirect Fourier transformation gave the overall physical dimensions of the complexes in solution, while the total scattering provided the oligomeric state of the molecules (see details in Supplementary Methods and Supplementary Figs 25 and 26). Analysis of the data assisted by molecular modelling then provided more detailed solution structures (see below and Supplementary Figs 27–29). SAXS measurements typically require a relatively high concentration; in this study 50 μM of each ON/POC unit was used, while the azidopeptidase was measured at 150 μM (3 × 50 μM). POC1 + POC2 + POC3 was measured at 50 μM, as well as at the lower concentrations of 3.6 and 7.2 μM.

The size of the self-assembled structures and the oligomeric state of ON1 + ON2 + ON3, azidopeptidase and individual POCs corresponded well with the expected values. Both ON1 + ON2 + ON3 and the azidopeptidase formed trimers, the latter with dimensions of the longest axis at ~7 nm and a cross section at ~2 nm, almost identical to the CoilVLaL and carbohydrate-templated peptide self-assembled structures26,51. ON1 + ON2 + ON3 also formed a trimer with a longest axis of ~7.5 nm and a cross section of ~2 nm, corresponding with a triple-helical DNA structure.

Studying the POCs individually, it was clear that POC1 formed a homo-dimer, while POC2 and POC3 formed homo-trimers, all with overall lengths of 13 nm, corresponding well with a DNA and peptide moiety. POC1 contains a rather short and rigid triplex-forming pyrimidine oligonucleotide moiety with half of the sequence modified by LNA nucleotides, while POC2 and POC3 contain a substantial proportion of purine nucleotide but no LNA. Some unexpected interactions and secondary structures may be formed for POC1, but not POC2 and POC3, which inhibit trimer formation. Furthermore, a thinner rod was no LNA. Some unexpected interactions and secondary structures may be formed for POC1, but not POC2 and POC3, which inhibit trimer formation. Furthermore, a thinner rod was

![Image](https://example.com/image.png)

Table 2 | SAXS studies and computational modelling.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Maximum distance (nm)*</th>
<th>Oligomeric state†</th>
<th>Rg (Å)</th>
<th>Experimental I(0)</th>
<th>Calculated I(0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ON1 + ON2 + ON3</td>
<td>7.5</td>
<td>Trimer</td>
<td>22.11 ± 0.05</td>
<td>3.95 x 10^-2</td>
<td>3.97 x 10^-2</td>
</tr>
<tr>
<td>Azidopeptidase</td>
<td>6.7</td>
<td>Trimer</td>
<td>19.93 ± 0.15</td>
<td>5.13 x 10^-3</td>
<td>5.19 x 10^-3</td>
</tr>
<tr>
<td>POC1 (TFO)</td>
<td>12.5</td>
<td>Dimer</td>
<td>36.59 ± 0.15</td>
<td>1.75 x 10^-2</td>
<td>1.46 x 10^-2</td>
</tr>
<tr>
<td>POC2</td>
<td>12.6</td>
<td>Trimer</td>
<td>38.49 ± 0.12</td>
<td>3.91 x 10^-2</td>
<td>3.49 x 10^-2</td>
</tr>
<tr>
<td>POC3</td>
<td>13.1</td>
<td>Trimer</td>
<td>41.68 ± 0.15</td>
<td>3.57 x 10^-2</td>
<td>3.40 x 10^-2</td>
</tr>
<tr>
<td>POC1 + POC2 + POC3 (7.2 μM)</td>
<td>12.7</td>
<td>Trimer</td>
<td>39.81 ± 0.23</td>
<td>1.81 x 10^-2</td>
<td>2.13 x 10^-2</td>
</tr>
<tr>
<td>POC1 + POC2 + POC3 (50 μM)</td>
<td>16.3</td>
<td>Dimer of trimers</td>
<td>48.01 ± 0.07</td>
<td>1.88 x 10^-1</td>
<td>1.81 x 10^-1</td>
</tr>
</tbody>
</table>

*As determined from the indirect Fourier transformation (pair distance distribution).
†As determined from the Guinier fit to the data. Experimental I(0) and Rg were derived from this.
Facility, while POC samples at 50 μM were measured at beamline B21 at the Diamond light Source (see Supplementary Information). Rewardingly, at the low concentrations, scattering corresponding to the POC1+POC2+POC3 trimer was observed. Interestingly, at high concentrations an apparent hexamer, interpreted as a dimer of trimers, assembled as the major component. Despite severe dissociation, both size-exclusion chromatography and gel electrophoresis showed the presence of both trimer and multimers, even at concentrations down to 0.5 μM (Supplementary Figs 17 and 40).

The scattering of the POC1+POC2+POC3 assembly and the pair distance distribution function (Supplementary Figs 25 and 26) showed that at low concentrations (3.6 and 7.2 μM) both the scattering extrapolated to zero angle and the maximum distances (13.0 and 12.7 nm) corresponded with a POC1+POC2+POC3 monomer. In contrast, at high concentration the mass (~60 kDa) and overall size (~16.5 nm) corresponded with a dimer of POC1+POC2+POC3. The longest distance was not double the distance found for the individual POCs, which indicated that either the dimer of trimers was not a fully linear structure, or that at least parts of the trimers interact and overlap.

Molecular modelling. We used molecular modelling to propose detailed POC1+POC2+POC3 models consistent with the SAXS measurements. Our approach (see Supplementary Methods and Supplementary Discussion section) yielded an ensemble of models for which the monomeric POC1+POC2+POC3 structure in Table 2b gave the best fit against the experimental SAXS data at low concentrations (3.6 and 7.2 μM), while the data recorded at 50 μM corresponded very well with the dimer of POC1+POC2+POC3 trimers also shown in Table 2b.

The calculated and experimental SAXS curves showed a very convincing agreement in the experimentally robust 0.01–0.2 Å⁻¹ region (see Supplementary Figs 27 and 28). Importantly, the trimer itself can be ruled out as a significant species in solution at the high concentration, due to its characteristic SAXS curve shape deviation in the low q range calculated for the MD structures (Supplementary Fig. 28c). Significant amounts of higher-order oligomers, for example, trimers of trimers, can also be excluded since the balancing amount of trimer required to yield the effective molecular weight consistent with SAXS would change the shape of the SAXS curve (Supplementary Figs 28c and 30–31). This point is illustrated with MultiFoXS calculations yielding an inferior curve shape for the composite trimer-of-trimer and trimer curve (Supplementary Fig. 32). A key feature of the POC1+POC2+POC3 dimer of trimers model in Table 2b (Supplementary Fig. 29) is that the two trimers interact hydrophobically via their linkers. This positions Lys residues in one trimer close to the DNA backbone of another, enabling electrostatic interactions between these moieties. The hydrophobic linker interaction was also found for other dimer of trimer models (not shown) with generally low γ (≤20), whereas other types of interaction dominated in dimer of trimers with higher γ, suggesting that the actual solution shape (or ensemble of solution shapes) for the POC1+POC2+POC3 dimer of trimers is well-represented by the model in Table 2b.

Transmission electron microscopy. The POC1+POC2+POC3 assembly was analysed by TEM (Fig. 4 and Supplementary Fig. 33. See also Supplementary Discussion and Supplementary Methods for details) at two different concentrations, namely ’3:2:2’ (3 μM in POC1 (TFO) and 2 μM in POC2 and POC3) and ’25:25:25’ (25 μM in each POC). The dimensions of the complexes were at the resolution limit of the microscope; hence detailed structural information was not extracted from the data. Class average images of the assemblies show an average higher aspect ratio of the complex at 25 μM than at lower concentration indicative of longer assemblies (Fig. 4). Most of the particles distinguishable at the lower concentration appear to be sized as trimers with a minor proportion appearing as dimerized trimers. In contrast, at 25 μM most of the POCs appear to be dimers of trimers (Fig. 4). It should be noted that drying and staining during the grid preparation procedure could alter the structure, but the increase in aspect ratio in the average images (Fig. 4) and the raw data (Supplementary Figs 34–39) is compatible with a transition from trimers to dimers of trimers at increased concentration. The TEM image analysis also suggests that the POCs have some internal flexibility, especially the 25:25:25, which make the class averaging more difficult. We note that though the TEM data are only indicative, they do give additional support to the observations from gel electrophoretic, CD and SAXS experiments that dimers of trimers dominate at higher concentration and single trimers at lower concentration.

Discussion. We envisioned that the combination of two fully orthogonal biomolecular self-assembly principles would enable the design of new protein-like structures and higher-order nanoscale-assemblies. Three POCs with molecular weights of 8.5–10.5 kDa were prepared by Cu-free alkyne azide coupling reactions. These POCs formed nano-assemblies which were characterized by ultraviolet thermal denaturation and annealing studies, gel electrophoresis, CD spectroscopy, SAXS and TEM. Ultraviolet and CD melting studies showed that duplexes and triple helices involving POCs are more stable than the non-peptide controls testifying to the importance of interactions between the peptide strands. In contrast, the apparent melting temperatures of the coiled coil peptide remained the same both in triple-helix POCs and as unconjugated peptide. CD spectroscopy further revealed...
that the triple-helical POC1 + POC2 + POC3 assembly displayed a high degree of \( \alpha \)-helicity, higher than that of the unconcatenated peptide. To the best of our knowledge, such \( \alpha \)-helicity values have never been reported in a purely aqueous solvent at ambient temperature which points to a helicity-transfer effect from the oligonucleotide triple-helix domain to the coiled coil peptide domain. SAXS performed at high POC concentration revealed the formation of a dimer of heterotrimers of triple-helix POCs, which was corroborated by computational simulation on the ensemble of POCs. At lower concentrations, the obtained SAXS data corresponded to the monomeric POC1 + POC2 + POC3 assembly. A higher-order assembly was also observed by gel electrophoresis. TEM analysis pointed to two different assembly modes, with a high degree of similarity between the two. A concentration of purified POCs was determined by ultraviolet absorbance at 260 nm (extinction coefficients in Supplementary Methods).

### Data availability
All relevant data are available from the corresponding authors on request.

### References

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Author contributions
The present work was designed and supervised by J.W. and K.J.J. C.L. performed synthesis and characterization of ONS and POCs, ultraviolet-melting studies and gel electrophoresis experiments; C.S.M. performed the synthesis of azidopeptide; S.R.M. carried out SAXS analysis; M.C.M.-M. and P.W.T. performed the CD experiments; N.J.C. carried out the molecular modeling calculations; and R.P.T. and J.K. performed the TEM studies. C.L., C.S.M., J.W. and K.J.J. co-wrote the manuscript draft. All authors contributed to data analysis and edited the manuscript.

Additional information
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