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Synthetic macromolecular peptide-mimetics with amino acid substructure residues as protein stabilising excipients†

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The clinical use of protein and peptide biotherapeutics requires fabrication of stable products. This particularly concerns stability towards aggregation of proteins or peptides. Here, we tested a hypothesis that interactions between a synthetic peptide, which is an aggregation-prone region analogue, and its homologous sequence on a protein of interest, could be exploited to design excipients which stabilise the protein against aggregation. A peptide containing the analogue of lysozyme aggregation-prone region (GILQINSRW) was conjugated to a RAFT agent and used to initiate the polymerisation of *N*-hydroxyethyl acrylamide, generating a GILQINSRW-HEA₉₀ polymer, which profoundly reduced lysozyme aggregation. Substitution of tryptophan in GILQINSRW with glycine, to form GILQINSRG, revealed that tryptophan is a critical amino acid in the protein stabilisation by GILQINSRW-HEA₉₀. Accordingly, polymeric peptide-mimetics of tryptophan, phenylalanine and isoleucine, which are often present in aggregation-prone regions, were synthesized. These were based on synthetic oligomers of acrylamide derivatives of indole-3 acetic acid (IND), phenylacetic acid (PHEN), or 2-methyl butyric acid (MBA), respectively, conjugated with hydrophilic poly(*N*-hydroxyethyl acrylamide) blocks to form amphiphilic copolymers denoted as IND_{*m*}-, PHEN_{*m*}- and MTB_{*m*}-*b*-HEA_{*n*}. These materials were tested as protein stabilisers and it was shown that solution properties and the abilities of these materials to stabilise insulin and the peptide IDR 1018 towards aggregation are dependent on the chemical nature of their side groups. These data suggest a structure–activity relationship, whereby the indole-based IND_{*m*}-*b*-HEA_{*n*} peptide-mimetic displays properties of a potential stabilising excipient for protein formulations.

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Introduction

The translation of proteins or peptides from biotechnology to biotherapeutic products offers potential treatments to a variety of diseases with unmet clinical need. The rationale for these biomolecules as therapeutics stems from their known mode of action, their inherent degradability as well as typical ‘drug attributes’ such as specificity and potency. This translation from an often complex and delicate macromolecule towards a medicine however requires fabrication of a stable product. This particularly concerns stability towards aggregation of protein or peptide molecules – the process by which unfolded molecules adopt a conformation that causes their clustering into

aggregates or/and fibrils.¹ Hence, solutions are required to ensure stability to different stress factors during all stages of development and use of peptide or protein formulations. There are currently over 130 protein biotherapeutics in clinical practice, covering disease indications from diabetes, haemophilia, multiple sclerosis, hepatitis C and many cancers.² These employ a range of stabilising strategies, including: addition of low-molecular weight compounds like amino acids glycine, proline and histidine,³ sugars like trehalose and sucrose, or polyols such as sorbitol. Covalent attachment of polyethylene glycol (PEG) to therapeutic proteins is another option which provides formulation stabilisation, and which can also impact positively on *in vivo* performance. PEGylated colony-stimulating factors, interferons, erythropoietin and mAbs^{4–6} are biotherapeutic products that have already reached clinical application. An alternative strategy is a non-covalent PEGylation of a protein, for example as shown by the use of cholanic acid-PEG to increase the half-life of recombinant human growth hormone (rh-GH) and recombinant human granulocyte colony stimulating factor (rh-G-CSF) *in vivo*,^{7,8} and tryptophan-PEG was used to

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Fig. 1 (a) Synthesis of HEA₉₀-GILQINSRW, and HEA₉₅-GILQINSRG; (b) synthesis of HEA_n as control polymers; (c) ¹H NMR (400 MHz, DMSO-d₆) spectra of obtained GILQINSRW-HEA₉₀ conjugation. Reagents and conditions: (a) DMF, DIPEA, rt; (b) DMF, piperidine, rt; (c) DMF, Fmoc-amino acid, HATU, DIPEA, rt; (d) CTA, HATU, TEA, DMF, rt; (e) DCM/TFE 8 : 2 v/v, rt; (f) *N*-hydroxyethyl acrylamide, V501, DMF, 70 °C; (g) AIBN, DMF, 80 °C; (h) 0.1 N HCl in hexafluoro-2-propanol (HFIP), rt.

Table 1 Composition, M_n , and dispersity of obtained peptides and polyHEA

Composition	$M_{n,THEO}^a$ (kDa)	$M_{n,NMR}$ (kDa)	$M_{n,SEC}^c$ (kDa)	D
HEA ₉₀ -GILQINSRW (1)	10.5	10.8 ^b	17.0	1.09
HEA ₉₅ -GILQINSRG (2)	10.3	12.1 ^b	14.8	1.13
HEA ₁₀₀	7.6	—	12.1	1.14

Composition is indicated by numbers in subscript. ^a Calculated from initial [HEA]:[CTA] and final monomer conversion. ^b Number of repeating units of HEA calculated from ¹H NMR spectra by comparing the integral of peptides' methyl groups with the hydroxyl peak of HEA repeating units. ^c Obtained from SEC in DMF + 0.1% LiBr (PMMA standards).

While the peptide GILQINSRW was insoluble in water, the polymer-peptide conjugate was freely soluble in both water and in phosphate buffer up to the highest tested concentration of 0.035 mg mL⁻¹. Accordingly, phosphate buffer was chosen as an appropriate medium for the lysozyme aggregation studies, in this case at a pH of 12.3 with assays conducted at room temperature, as these are conditions known to denature lysozyme.^{29,30} This approach assumes that these conditions promote unfolding of the protein exposing its APR, which

makes it more accessible to APR from other lysozyme protein molecules and to the APR-like sequence from HEA₉₀-GILQINSRW.

The results of the lysozyme aggregation study are shown in Fig. 2 and confirm the formation of large aggregates in control samples containing only lysozyme. Conversely, in the presence of HEA₉₀-GILQINSRW (1 : 1 mol with respect to lysozyme) the onset of aggregation was delayed by 10 hours, and within 24 hours



Fig. 2 Aggregation assay for lysozyme (10 mg mL⁻¹) in the presence of HEA₉₀-GILQINSRW, HEA₉₅-GILQINSRG, and HEA₁₀₀ in 100 mM phosphate buffer pH 12.3; molar ratio of peptides and HEA₁₀₀ to lysozyme was 1 : 1. Lysozyme aggregation assessed by turbidimetry at $\lambda = 500$ nm, readings were taken every 30 min for 24 h.





Fig. 3 (a) Synthesis of IND_m-, PHEN_m-, MTB_m-b-HEA_n block copolymers. Reagents and conditions: (a) AIBN, CTA, DMF, 80 °C; (b) *N*-hydroxyethyl acrylamide, V501, DMF, 70 °C; (c) ¹H NMR (DMSO-d₆, 400 MHz) spectrum of IND₃-HEA₉₅ as a representative spectrum of the synthesised block copolymers; SEC chromatograms of IND_m-b-HEA_n copolymers with (c) shorter and (d) longer hydrophilic blocks, using DMF with 0.1% LiBr as the mobile phase. Spectra and SEC chromatograms of all polymers are shown in Sections S5.3.1 and S5.3.2 in the ESI.†

Table 2 *M_n* and dispersity of IND_m-, PHEN_m-, MTB_m-b-HEA_n materials synthesised in this work

Composition	<i>M_n</i> ,THEO ^a (kDa)	<i>M_n</i> ,NMR (kDa)	<i>M_n</i> ,SEC ^e (kDa)	<i>D</i>	Composition	<i>M_n</i> ,THEO ^a (kDa)	<i>M_n</i> ,NMR (kDa)	<i>M_n</i> ,SEC ^e (kDa)	<i>D</i>
IND ₁ -b-HEA ₃₇	5.5	5.0 ^b	8.7	1.07	IND ₁ -b-HEA ₁₀₀	9.0	8.7 ^b	13	1.08
PHEN ₁ -b-HEA ₃₇	5.1	4.8 ^c	9.0	1.07	PHEN ₁ -b-HEA ₁₀₀	12	12.2 ^c	18.6	1.08
MTB ₁ -b-HEA ₃₇	5.9	4.8 ^d	10.4	1.05	MTB ₁ -b-HEA ₁₁₁	13.1	13.2 ^d	19.8	1.09
IND ₃ -b-HEA ₅₃	5.4	6.7 ^b	11.7	1.09	IND ₃ -b-HEA ₉₈	11.5	12 ^b	17	1.11
PHEN ₃ -b-HEA ₄₅	5.4	6.2 ^c	9.6	1.07	PHEN ₃ -b-HEA ₉₉	11.7	12.5 ^c	17.5	1.06
MTB ₃ -b-HEA ₄₂	6.4	7.3 ^d	10.9	1.05	MTB ₃ -b-HEA ₈₂	10.2	10.5 ^d	16.8	1.07
IND ₁₀ -b-HEA ₄₀	6.1	7.7 ^b	10.5	1.15	IND ₁₀ -b-HEA ₉₅	10.7	14.1 ^b	18.4	1.11
PHEN ₁₀ -b-HEA ₃₈	6.8	7.0 ^c	10.7	1.08	PHEN ₁₀ -b-HEA ₈₈	12.6	12.9 ^c	17.4	1.07
MTB ₁₀ -b-HEA ₄₃	6.7	7.2 ^d	10.0	1.07	MTB ₁₀ -b-HEA ₁₀₅	12.5	15.0 ^d	18.7	1.07
HEA ₃₆	4.5		8.5	1.04	HEA ₁₀₀	13		12.1	1.14

^a Calculated from initial [HEA]:[CTA] and final monomer conversion. ^b Number of repeating units of HEA monomers calculated by ¹H NMR, in DMSO-d₆, by comparing the integral of indole aromatic. ^c Number of repeating units of HEA monomers calculated by ¹H NMR, in DMSO-d₆, by comparing the integral of methylene. ^d Number of repeating units of HEA monomers calculated by ¹H NMR, in DMSO-d₆, by comparing the integral of methylbutyryl methyl peaks with the hydroxyl peak of HEA repeating units. ^e Obtained from SEC in DMF + 0.1% LiBr (PMMA standards).





Fig. 4 Size distribution (volume%) of copolymers' self-assemblies (1 mg mL^{-1}) in DI water as determined by DLS.

Table 3 Hydrodynamic diameter measured by DLS of IND_m -, PHEN_m -, and MTB_m - b - HEA_n copolymers reported from volume distribution. Polydispersity indices are provided in brackets; materials were analysed at 1.0 mg mL^{-1} in DI water

Polymer:	IND_1 - b - HEA_{37}	PHEN_1 - b - HEA_{37}	MTB_1 - b - HEA_{37}	IND_1 - b - HEA_{100}	PHEN_1 - b - HEA_{100}	MTB_1 - b - HEA_{111}
Size (PDI) nm	4.43 (0.26)	3.28 (0.62)	3.15 (0.36)	6.05 (0.11)	5.69 (0.05)	6.81 (0.43)
Polymer:	IND_3 - b - HEA_{53}	MTB_3 - b - HEA_{42}	MTB_3 - b - HEA_{42}	IND_3 - b - HEA_{98}	PHEN_3 - b - HEA_{99}	MTB_3 - b - HEA_{82}
Size (PDI) nm	5.54 (0.18)	3.53 (0.07)	4.73 (1.62)	5.21 (0.27)	6.23 (0.86)	5.40 (1.0)
Polymer:	IND_{10} - b - HEA_{40}	PHEN_{10} - b - HEA_{38}	MTB_{10} - b - HEA_{43}	IND_{10} - b - HEA_{95}	PHEN_{10} - b - HEA_{88}	MTB_{10} - b - HEA_{105}
Size (PDI) nm	9.73 (0.16)	9.71 (0.18)	6.54 (0.20)	14.28 (0.15)	12.03 (0.16)	5.38 (0.33)

Modulation of insulin aggregation by block copolymers

After identifying the key role of tryptophan in the HEA_{90} -GILQINSRW stabilisation of lysozyme, we studied tryptophan peptide-mimetic oligomers based on indole-3 acetic acid (IND_m - b - HEA_n), on the basis that the indole ring contributes the defining physicochemical properties of tryptophan.³¹ Unfortunately, under the alkaline conditions that induce lysozyme aggregation, IND_m -, PHEN_m - and MTB_m - b - HEA_n materials failed to show any stabilizing effect (Fig. S32 and S33, Section S6 in ESI[†]). Further analysis revealed that these aggregation favouring conditions (pH 12.3) induce hydrolysis of the ester groups linking the pendant indole group to the polymer backbone; the ^1H NMR spectrum of IND_{10} - b - HEA after incubation under such conditions displayed no indole aromatic protons peaks between 6.9–7.3 ppm (Spectrum S34, Section S6 in the ESI[†]).

Accordingly, we selected insulin as a model protein to replace lysozyme in the aggregations studies as it is well-established that

the aggregation of insulin is initiated at pH around 5.3, corresponding to the protein isoelectric point.³⁷ The residues of insulin B-chain including GB8, SB9, VB12, EB13, YB16, GB23, FB24, FB25, YB26, and TB27 are believed to play an important role in insulin self-assembly.³⁸ The impact of the peptide-mimetic materials synthesized in this work on the aggregation of insulin is shown in Fig. 6. Only 17% of insulin (0.34 mg mL^{-1} out of 2 mg mL^{-1}) remained in a solution after incubation at conditions inducing its aggregation. However, the addition of IND_3 - and IND_{10} - b - HEA_m polymers at polymer:peptide molar ratio of 10 prevented aggregation very efficiently – almost 100% of insulin remained in its non-aggregated state after 20 h. Conversely, this effect was not observed for IND_1 - b - HEA_n which possesses only one indole group. For PHEN_m -based copolymers, only the longest copolymer, PHEN_{10} - b - HEA_{88} , reduces aggregation (61% non-aggregated insulin retained), when compared to HEA_{100} control polymers (only 24% of residual insulin in solution).



Fig. 5 Surface tension measurements of representative copolymers IND_3 - b - HEA_{98} and IND_{10} - b - HEA_{95} carried out in water by pendant drop method.³⁶





Fig. 6 Insulin aggregation in the presence of IND_m-, PHEN_m- and MTB_m-b-HEA_n materials. Concentration of insulin remaining in a solution after incubation in the aggregation inducing conditions (pH 5.2) for 20 h without and with synthesised copolymers at different molar ratio; the initial concentration of insulin was 2 mg mL⁻¹. Higher values in the graph correspond to better protein stabilisation and hence reduced aggregation.

No measurable impact against insulin aggregation is seen for copolymers containing isoleucine-mimicking groups – MTB_m-b-HEA_n.

Interaction of peptide-mimetic oligomers with insulin.

In the next step potential effects of the IND₁₀-based oligomers on the secondary structure of insulin were assessed by circular dichroism (CD). The analysis of samples in the presence of IND₁₀-b-HEA₉₅ produced poor signal-to-noise ratio, likely due to the presence of indole groups, as reported previously.³⁹ The analysis hence measured the CD profile after separation of insulin and IND₁₀-b-HEA₉₅. Whilst this experiment cannot inform directly on secondary structure alterations that may be occurring during insulin interactions with stabilizing IND₁₀-b-HEA₉₅, it however provides an insight to whether these interactions induce irreversible changes of the protein secondary structure (Fig. S31, ESI†). The profile obtained from the ‘native’ insulin, *i.e.* before any manipulation, exhibits two negative

peaks, at 208 nm and 222 nm, as previously described for bovine insulin, and is typical of an α -helix secondary structure.⁴⁰ A similar profile is seen for the sample subjected to HPLC purification. The two samples taken from insulin aggregation experiments in the presence of IND₁₀-b-HEA₉₅ at 10 : 1 and 5 : 1 insulin molar ratios also show $[\theta]$ vs. wavelength profiles similar to that of native insulin. The experiment hence indicates that the stabilizing IND₁₀-b-HEA₉₅ peptide-mimetic does not cause irreversible changes in the protein secondary structure.

Moderation of IDR 1018 aggregation by block copolymers

To exemplify the potential of our synthetic peptide-mimetic materials to moderate aggregation of peptides, the IDR 1018 peptide, consisting of the amino acid sequence VRLIVAV-RIWRR was selected. This peptide has been reported to show antimicrobial and immunomodulatory activities,^{41–43} but clinical applications have been hampered by its tendency to



Fig. 7 The concentration of IDR 1018 remaining in a solution after incubation in aggregation conditions (100 mM phosphate buffer, pH 7.2) for 5 h without and with synthesised copolymers at 1 : 1 molar ratio; the initial concentration of the peptide was 0.153 mg mL⁻¹. Higher values in the graph correspond to better protein stabilisation and hence reduced aggregation.



