Self-Assembling VHH-Elastin-Like Peptides for Photodynamic Nanomedicine

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Supporting Information

ABSTRACT: Recombinant llama heavy-chain antibody fragments (VHHs) are promising tools in the field of targeted nanomedicine. 7D12, a VHH against the epidermal growth factor receptor (EGFR) that is overexpressed in various cancers, has been evaluated as an effective cancer-targeting VHH in multiple studies. The small size of VHHs (15–20 kDa) results in a low circulation half-life, which can be disadvantageous for certain applications. A solution to this problem is to attach VHHs to the surface of nanoparticles to increase the hydrodynamic radius of the conjugate. This approach simultaneously allows the incorporation of different VHHs and other targeting moieties and therapeutic components into one structure, creating multispecificity and versatility for therapy and diagnosis. Here, we present the construction of highly defined 7D12-containing nanoparticles by utilizing thermo-responsive diblock elastin-like peptides that reversibly self-assemble into micellar structures. The resulting particles have a hydrodynamic radius of 24.3 ± 0.9 nm and retain full EGFR-binding capacity. We present proof of concept of the usability of such particles by controlled incorporation of a photosensitizer and show that the resulting nanoparticles induce EGFR-specific light-induced cell killing. This approach is easily extended to the controlled incorporation of various functional modules, improving therapy and diagnosis with targeted nanomedicine.

INTRODUCTION

The variable region of heavy-chain antibodies found in cameloids, called VHH, is of great interest to the field of nanomedicine.1–3 VHHs are thermo- and pH-stable proteins that are well tolerated by the human immune system. Their affinity can equal or even supersede that of “conventional” antibodies. In combination with cytotoxic agents, tumor-targeting VHHs can specifically recognize and kill cancer cells.4,5 Although their small size of 15–20 kDa allows deeper tissue penetration than conventional antibodies, it also results in a low circulation half-life.

Nanoparticles decorated with VHHs have been developed to overcome the short blood-circulation time by increasing the hydrodynamic radius; the nanoparticle structure furthermore enables increased and more versatile drug loading.6–8 Decoration with VHHs usually follows particle formation, and encapsulation or attachment of a desired payload is typically achieved during particle formation or via an additional coupling step. This procedure makes it difficult to precisely assess and reproducibly control the resulting VHH concentration on the particles’ surface and the VHH-to-payload ratios. Controlling these parameters is essential to achieve maximum efficacy with minimal side effects. Thus, there is a clear need for optimally defined and controlled VHH-displaying nanoparticles.

Elastin-like peptides (ELPs) are biocompatible polypeptides that form amorphous coacervates in a temperature-dependent fashion.9–11 They are composed of repeating pentameric units with the sequence glycine-X-glycine-valine-proline (GXGVP), where X can be any amino acid.11,12 ELPs reversibly transform from a soluble, disordered state below the transition temperature to an assembled state consisting of type-II β-turns, type-I β-turns, and β-strands above the transition temperature.13–16 This behavior is thermodynamically driven: at the transition temperature, solvation of the protein backbone becomes entropically unfavorable. The conformational change and exposure of hydrophobic residues followed by assembly results in liberated water molecules, lowering the total energy of the system. Further increases in temperature enhance this effect. This so-called lower critical solution temperature (LCST) highly depends on the nature of the guest residue X, with hydrophobic residues raising the LCST and hydrophilic residues lowering it. ELP length, concentration, and presence of salts also affect the LCST.17

VHH-ELP fusion proteins have previously been synthesized with the aim to allow easy purification via temperature cycling.

Received: January 13, 2017
Revised: March 3, 2017
Published: March 7, 2017

DOI: 10.1021/acs.biomac.7b00064
Biomacromolecules 2017, 18, 1302−1310
followed by VHH cleavage via introduced protease-sensitive tags.\textsuperscript{18} ELP-based nanoparticles have been prepared out of amphiphilic block copolymers, either by employing ELP diblock polypeptides with different guest residues and, hence, different LCSTs\textsuperscript{9,10,19} or by coupling ELPs with low LCST to hydrophilic polymers such as poly(ethylene glycol).\textsuperscript{20} Given the excellent biocompatible properties of ELPS,\textsuperscript{21,22} we envisioned the possibility of integrating VHH-ELP expression systems with the nanoparticle-forming potential of ELPS.

Here we report the use of an ELP diblock polypeptide (ELP\textsuperscript{D8}) to create self-assembling theranostic VHH-nanoparticles. The ELP\textsuperscript{D8} was composed of a “hydrophilic” and a “hydrophobic” block, terms that relate to the solvation state of the ELP block at physiological conditions. The hydrophobic block consisted of 60 pentamers with alanine or glycine guest residues in a ratio of 3:2 (see SI). The hydrophilic block contained 60 pentamers with isoleucine as guest residues. We used the VHH 7D12 that targets the epidermal growth factor receptor (EGFR),\textsuperscript{23,24} Fc5, an unrelated VHH directed against the endothelial receptor Cdc50A, was used as control.\textsuperscript{25} Well-defined composite nanoparticles were reproducibly made by combining 7D12-ELP\textsuperscript{D8} or Fc5-ELP\textsuperscript{D8} fusion proteins with ELP\textsuperscript{D8} as molecularly dissolved species at predetermined ratios, followed by heating the solution above the LCST of the hydrophobic block (Figure 1). The 7D12-decorated ELPs were expressed as fusion products with ELP\textsuperscript{D8} and 7D12-CLPETG-HIS-VSV, hereafter, 7D12, was produced as a control for the in vitro studies. The gene sequences encoding for ELP\textsuperscript{D8}, pelB-Fc5-ELP\textsuperscript{D8} and pelB-7D12-ELP\textsuperscript{D8} were cloned into pET-24a(+) (Novagen) expression vectors,\textsuperscript{26} by recursive directional ligation,\textsuperscript{2} transformed into E. coli BLR(DE3) cells and grown on agar plates containing 30 µg/mL kanamycin overnight at 37 °C. A single colony was grown overnight at 30 °C, 250 rpm in LB medium containing 50 µg/mL kanamycin and 0.5% w/v d-glucose. The overnight culture was diluted to an OD\textsubscript{600} of 0.1 in filter-sterilized AIM TB medium (Formedium) containing 6 g/L glycerol, 0.005% antifoam 204, and 50 µg/mL kanamycin. Cells were grown at 300 rpm at 37 °C for 20 h. For 7D12-ELP\textsuperscript{D8} and Fc5-ELP\textsuperscript{D8}, the culture was shifted to 30 °C after 4 h of growth.

The pHENIX-7D12-C-LPETG-HIS-VSV plasmid was transformed in E. coli strain ER2566. Cells were grown at 37 °C in 2xTY medium containing 3.5% (w/v) glycerol and 50 µg/mL ampicillin until an OD\textsubscript{600} of 0.6–0.8. Protein expression was induced with 1.0 mM isopropyl β-D-thiogalactoside (IPTG, Serva, Heidelberg, Germany) at 30 °C for 2.5 h.

### MATERIALS AND METHODS

All chemicals and consumables were obtained by Sigma-Aldrich, unless specified otherwise.

#### Cloning and Protein Expression

The VHHS 7D12 and Fc5 were used in this study; 7D12 is directed against EGFR, and Fc5 targets the luminal brain endothelial cell protein Cdc50A.\textsuperscript{26} 7D12 and Fc5 were expressed as fusion products with ELP\textsuperscript{D8} and 7D12-CLPETG-HIS-VSV, hereafter, 7D12, was produced as a control for the in vitro studies. The gene sequences encoding for ELP\textsuperscript{D8}, pelB-Fc5-ELP\textsuperscript{D8} and pelB-7D12-ELP\textsuperscript{D8} were cloned into pET-24a(+) (Novagen) expression vectors,\textsuperscript{26} by recursive directional ligation,\textsuperscript{2} transformed into E. coli BLR(DE3) cells and grown on agar plates containing 30 µg/mL kanamycin overnight at 37 °C. A single colony was grown overnight at 30 °C, 250 rpm in LB medium containing 50 µg/mL kanamycin and 0.5% w/v d-glucose. The overnight culture was diluted to an OD\textsubscript{600} of 0.1 in filter-sterilized AIM TB medium (Formedium) containing 6 g/L glycerol, 0.005% antifoam 204, and 50 µg/mL kanamycin. Cells were grown at 300 rpm at 37 °C for 20 h. For 7D12-ELP\textsuperscript{D8} and Fc5-ELP\textsuperscript{D8}, the culture was shifted to 30 °C after 4 h of growth.

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### Protein Extraction and Purification

Cells were collected by centrifugation at 2000 g, 4 °C for 30 min. For cytoplasmic extraction, 1 g of wet cell pellet was resuspended in 2 mL of lysis buffer (50 mM Tris-HCl pH 8.0, 25 mM NaCl, 1 mM EDTA, 0.1 mM PMSF, Complete Protease Inhibitor Cocktail, 0.5 mg/mL lysozyme) and incubated for 4 h at 4 °C. Lysis was followed by sonication on a Branson Sonifier 250 (power level 2–4, 12 cycles of 10 s sonication, 10 s breaks). Cell debris was collected by centrifugation at 15,000 g at 4 °C for 15 min. Residual DNA was precipitated by adding 0.5% w/v poly(ethylene imine) and removed by centrifugation at 15,000 g at 4 °C for 15 min. ELP\textsuperscript{D8} was precipitated by adding a saturated solution of (NH\textsubscript{4})\textsubscript{2}SO\textsubscript{4} up to 10–25 v/v%. Proteins were collected by centrifugation at 15,000 g at 4 °C for 15 min. The pellet was resuspended in phosphate buffered saline and centrifuged to remove insoluble contaminants at 15,000 g at 4 °C for 20 min. This cycle was repeated until sufficient purity was achieved, usually after 2–4 cycles. ELPs were resuspended in Milli-Q, desalted on a HiPrep 26/10 (GE Healthcare Life Sciences) with an AKTA Explorer 10 (GE Healthcare Life Sciences) at 1 mL/min Milli-Q. Residual salt concentration was below 0.001 mg/mL, as determined by conductivity. The ELP solution was filter-sterilized with 0.22 µm PES syringe filters (Nalgene) and freeze-dried. Yield was determined by weighing and varied around 43 mg/L culture (Table 1).

For periplasmic extraction of 7D12, 7D12-ELP\textsuperscript{D8} and Fc5-ELP\textsuperscript{D8}, 1 g of wet cell pellet was resuspended in 10 mL of extraction buffer A (0.2 M TRIS pH 8.0, 0.5 mM EDTA, 20 w/v% sucrose, 0.1 mM PMSF, Complete Protease Inhibitor Cocktail) and incubated for 30 min at 4 °C. Cells were pelleted by centrifugation at 2000 g for 30 min and 7D12-ELP\textsuperscript{D8} and Fc5-ELP\textsuperscript{D8}.

#### Table 1. Overview of Proteins Used in This Study

<table>
<thead>
<tr>
<th>Construct</th>
<th>Yield (mg/L)</th>
<th>Theoretical mass (Da)</th>
<th>Found mass (Da)</th>
<th>Labeling efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELP\textsuperscript{D8}</td>
<td>43</td>
<td>48198</td>
<td>48198</td>
<td>NA</td>
</tr>
<tr>
<td>7D12-ELP\textsuperscript{D8}</td>
<td>33</td>
<td>63049</td>
<td>63031 and 63049</td>
<td>NA</td>
</tr>
<tr>
<td>Fc5-ELP\textsuperscript{D8}</td>
<td>47</td>
<td>61903</td>
<td>61904</td>
<td>NA</td>
</tr>
<tr>
<td>Alexa47\textsuperscript{a}</td>
<td>49</td>
<td>49307</td>
<td>49306</td>
<td>61 ± 2</td>
</tr>
<tr>
<td>PS-ELP\textsuperscript{D8}</td>
<td>49</td>
<td>49951</td>
<td>49951</td>
<td>Quantitative</td>
</tr>
<tr>
<td>7D12-ELP\textsuperscript{D8}</td>
<td>NA</td>
<td>63475</td>
<td>63457 and 63475</td>
<td>89 ± 2</td>
</tr>
<tr>
<td>Fc5-ELP\textsuperscript{D8}</td>
<td>NA</td>
<td>62330</td>
<td>62332</td>
<td>88 ± 3</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Yield specifies obtained product per liter of bacterial culture. The theoretical mass was determined with ExPASy (http://www.expasy.org/), excluding the N-terminal methionine for ELP\textsuperscript{D8} or the pelB sequence for 7D12-ELP\textsuperscript{D8} and Fc5-ELP\textsuperscript{D8} (see SI). Mass found after deconvolution of mass spectrum. \textsuperscript{b}Percentage of labeled protein.
at 4 °C and the supernatant collected. The extraction was repeated with extraction buffer B (0.2 M Tris pH 8.0, 15 mM MgSO₄, Complete Protease Inhibitor Cocktail). Both supernatants were pooled before further processing. ELPs were precipitated as described above. Yield was determined by integration of the absorbance at 280 nm after separation with a Bio-Sec 5 300 Å column on an Agilent Bio-Inert HPLC with a flow rate of 1 mL/min PBS (Table 1). Aliquots were flash-frozen in liquid nitrogen and stored at −80 °C. 7D12 was purified using Ni-NTA sepharose (IBA, Goettingen, Germany) by incubating the extraction supernatant with pre-equilibrated Ni-NTA sepharose for 1 h at 4 °C, and after washing, the proteins were eluted with 500 mM imidazole. The eluate was dialyzed against 50 mM Tris-buffer at 0.4 mL/min; the eluted mass was determined by ESI-TOF on a JEOL AccuTOF. Size-Exclusion Chromatography Followed by Multiangle Light Scattering (SEC-MALS). For SEC-MALS, the samples were separated on a Bio-Sec 5 1000 Å column (Agilent) at 0.4 mL/min with a flow rate of 1 mM/ min PBS alone was added, was taken as control. Light scattering data was collected at 4 and 37 °C. Aggregation was determined by integration of the absorbance at 280 and 495 nm after separation with a Bio-Sec 5 300 Å column on an Agilent Bio-Inert HPLC with a flow rate of 1 mL/min 0.1 M NH₄HCO₃ pH 8.62 (Table 1). Mass was determined by ESI TOF. 7D12FL-ELPDB and Fc5FL-ELPDB were flash-frozen in liquid nitrogen and stored at −80°C. See Figure S1 for a fluorescent SDS PAGE analysis.

**Dynamic Light Scattering and Stability of ELP Particles in Human Serum.** Samples were diluted to a final concentration of 2 μM in PBS. Measurements were performed on a Malvern Zetasizer Nano. Samples were incubated for 5 min at 37 °C before data collection. Reported values are averages of three independent measurements. For particle stability, 10 μM of 2% 7D12FL-ELPDB, 98% PS-ELPDB was added to human serum. Human serum alone, to which an equal volume of PBS alone was added, was taken as control. Light scattering data was collected at 4 and 37 °C. Aggregation was inspected visually. Reported values are averages of three independent measurements.

**Cell Culture.** Human epidermoid carcinoma A431 cells with amplification of EGFR and high grade astrocytoma E98 cells without EGFR expression were cultured in DMEM (Lonza, Basel, Switzerland), supplemented with 10% FCS (Gibco) and 40 μg/mL gentamycin (Centrafarm, Etten-Leur, The Netherlands). Cells were cultured at 37 °C in 5% CO₂ in a humidified atmosphere.

**Flow Cytometry.** To determine functionality of 7D12FL-ELPDB monomers, binding to A431 and E98 cells was determined under noninternalizing conditions at 4 °C. A431 and E98 cells were dissociated from culture flasks using 10 mM EDTA in PBS and transferred to V-bottom shaped 96-well microplates (BD Biosciences, Franklin Lakes, NJ, U.S.A.) at 5 × 10⁵ cells per well. Cells were blocked with PBA (PBS, 0.5% BSA and 2% FCS) for 10 min at 4 °C, after which they were incubated with 1 μM 7D12FL-ELPDB or controls Fc5FL-ELPDB and 7D12FL in PBA for 30 min at 4 °C. After washing twice with cold PBA, cell-associated fluorescence was quantified on the CytoF low flow cytometer (Beckman Coulter, Fullerton, CA, U.S.A.) with parameter FL-1. To determine uptake of VHH functionalized ELP nanoparticles and compare this to monomeric VH4, A431 and E98 cells were grown to 80% confluency in 8-well chamber Lab-Tek chambers (NUNC) after which cells were incubated with a concentration range of prewarmed 7D12FL; 10% 7D12FL-ELPDB, 5% Alexa647-ELPDB, 85% ELPDB particles or 10% Fc5FL-ELPDB, 5% Alexa647-ELPDB, 85% ELPDB particles in DMEM with 10% FCS for 30 min at 37 °C. Cells were washed twice with warm DMEM with 10% FCS, dissociated with trypsin and taken up in PBS, and cell associated fluorescence was quantified on the CytoF low flow cytometer with parameters FL-1 and FL-8. Experiments were performed in triplicate and statistical significance was tested with an unpaired Student’s t-test. Furthermore, cells were incubated after incubation with ELPDB particles (or equimolar VHH of 7D12FL) on the EVOS microscope using LED cubes GFP (Fluorescein) and Cy5 (Alexa647).

In **Vitro PDT Assays.** A431 and E98 cells were cultured in clear 96 wells plates until 80% confluency. Then cells were incubated with a concentration range of prewarmed 7D12FL or 2% 7D12FL-ELPDB, 98% PS-ELPDB particles or 2% Fc5FL-ELPDB, 98% PS-ELPDB particles in DMEM with 10% FCS for 30 min at 37 °C. Cells were washed twice with warm DMEM with 10% FCS, dissociated with trypsin and taken up in PBS, and cell associated fluorescence was quantified on the CytoF low flow cytometer with parameters FL-1 and FL-8. Experiments were performed in triplicate and statistical significance was tested with an unpaired Student’s t-test. Furthermore, cells were incubated after incubation with ELPDB particles (or equimolar VHH of 7D12FL) on the EVOS microscope using LED cubes GFP (Fluorescein) and Cy5 (Alexa647).
assays, and results were expressed as cell viability relative to untreated illuminated cells.

To examine selectivity of PDT-induced cytotoxicity, $5 \times 10^5$ cells were labeled with DiO (A431) or DID (E98) dye (Life Technologies, Thermo Fisher Scientific, Waltham, MA, U.S.A.) according to manufacturers’ protocol. A431, E98, or 1:1 mixtures of the cells were plated and subjected to PIT with 30 nM of the particles or equimolar VHH concentrations of the 7D12PS control as described above. Four hours after illumination, cells were incubated with 1 μg/mL propidium iodide (Thermo Fisher Scientific, Waltham, MA, U.S.A.) in PBS for 15 min. Cells were visualized with the EVOS microscope using the RFP channel (propidium iodide), the GFP channel (DiO-labeled cells), and the Cy5 channel (DiD-labeled cells).

Stability of ELPDB Particles in Human Serum. Stability of ELPDB particles in serum was evaluated further by incubating 96 nM [ELP] 2% 7D12FL-ELPDB, 98% PS-ELPDB or 2% Fc5FL-ELPDB, 98% PS-ELPDB in freshly obtained human serum (HS) for either 30 min, 2 h, or 4 h at 37°C. Subsequently, the 96 nM stocks were diluted in DMEM with 10% FCS, and PDT assays were performed with A431 cells as described earlier. Cell viability was compared to controls incubated with diluted serum without PS-ELPDB micelles and with PS-ELPDB micelles directly diluted in DMEM with 10% FCS.

RESULTS AND DISCUSSION

VHH-ELPDB’s were prepared by cloning cDNA sequences coding for 7D12 and Fc5 in frame with ELPDB. An intervening cysteine residue was introduced as a handle for maleimide-based modification. Fusion proteins were successfully expressed in BLR(DE3) Escherichia coli cells by autoinduction (Figure 2). The sequences were preceded by a pelB leader sequence to direct the protein to the periplasm of E. coli. The slightly oxidative milieu in the bacterial periplasm allowed the proper formation of internal disulfide bonds present in 7D12 and Fc5. The proteins were purified by inverse-transition cycling, ELPDB and VHH-ELPDB fusion proteins were obtained in >95% purity with 20–50 mg/L yield (Table 1, Figure 2A). Molecular masses of the protein samples were measured via electrospray ionization time-of-flight spectrometry (ESI-ToF) and agreed well with the predicted masses (Figure 2B). The N-terminal formyl methionine of ELPDB was cleaved off as expected.29 For 7D12-ELPDB and Fc5-ELPDB, an additional peak was found. 7D12 contains an N-terminal glutamine, which is known to be converted in an autocatalytic or enzymatic step to

Figure 2. Characterization of expressed proteins and formed nanoparticles: (A) SDS-PAGE of ELPDB (silver-stained, absence of aromatic amino acids in the ELP prevents Coomassie Brilliant Blue (CBB) staining), 7D12-ELPDB, and Fc5-ELPDB (stained with CBB). (B) Mass spectra and deconvoluted masses of (a) ELPDB, (b) 7D12-ELPDB, and (c) Fc5-ELPDB. (C) Size-exclusion chromatography coupled to multiangle light scattering of nanoparticles containing 10% 7D12-ELPDB. (D) Evaluation of nanoparticle stability as a function of the fraction of 7D12-ELPDB or Fc5-ELPDB. X-axis represents the ratio of VHH-ELPDB to ELPDB in the micelles.
pyroglutamate, resulting in the loss of ammonia, explaining the 18 Da difference.30 Fc5-ELPDB, which does not contain N-terminal glutamine, did not show this side product (Table 1).

ELPDB nanoparticles were stable between 25 and 55 °C (Figure S2). For characterization, purified ELPDB was heated to 37 °C after which hydrodynamic radius, radius of gyration, and molecular weight were determined by size-exclusion chromatography, followed by multiangle light scattering (Figures 2C and S3). The hydrodynamic radius was approximately 24 nm (Table 2). The ratio of radius of gyration to hydrodynamic radius, an indication of the morphology of particles, was close to the theoretical value of a homogeneous sphere (0.778).31,32

Table 2. Results from SEC-MALS Measurements of the Different Nanoparticle Formulations

<table>
<thead>
<tr>
<th>Sample</th>
<th>R_h (nm)</th>
<th>R_g (nm)</th>
<th>ρ</th>
<th>Mass (kDa)</th>
<th>Monomers per micelle</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELPDB</td>
<td>24.0 ± 0.5</td>
<td>17.2 ± 0.1</td>
<td>0.72 ± 0.02</td>
<td>10300 ± 15</td>
<td>214</td>
</tr>
<tr>
<td>10% 7D12-ELPDB</td>
<td>24.6 ± 0.6</td>
<td>17.4 ± 0.1</td>
<td>0.71 ± 0.02</td>
<td>9958 ± 17</td>
<td>200</td>
</tr>
<tr>
<td>10% Fc5-ELPDB</td>
<td>24.3 ± 0.6</td>
<td>19.8 ± 0.3</td>
<td>0.81 ± 0.02</td>
<td>10470 ± 16</td>
<td>211</td>
</tr>
</tbody>
</table>

aHydrodynamic radius. bRadius of gyration. cRadius of gyration divided by the hydrodynamic radius. dAverage molecular mass. eMonomers per micelle calculated with the weighted average molecular mass of ELPDB particles and monomers. See Figure S3 for SEC-MALS data.

Figure 3. Cellular binding and uptake of VHHFL-ELPDB monomers and micelles, respectively. (A) Cell-associated FL fluorescence as determined with flow cytometry after cold (4 °C) incubation with 1 μM 7D12FL, 7D12FL-ELPDB, or Fc5FL-ELPDB monomers. (B) Cell-associated FL and Alexa647 fluorescence, as determined with flow cytometry after warm (37 °C) incubation with 10 μM (refers to total ELPDB concentration) of 7D12FL-Alexa647-ELPDB micelles or Fc5FL-Alexa647-ELPDB micelles. Note that there is some unexplained nonspecific background binding of AlexaELPDB, but not of VHHFL-ELPDB. (C) Cell-associated FL and Alexa647 fluorescence as determined with flow cytometry after warm (37 °C) incubation of A431 cells with a concentration range of 7D12FL-Alexa647-ELPDB micelles or Fc5FL-Alexa647-ELPDB micelles. * indicates significance with p < 0.05, ** indicates significance with p < 0.01, *** indicates significance with p < 0.001.
In order to determine the maximum possible functionalization degree of the nanoparticles with VHH, we proceeded by systematically mixing ELPDB with different percentages of 7D12-ELPDB or Fc5-ELPDB. We observed a transition point at
50% 7D12FL-ELPDB and 60% Fc5FL-ELPDB, respectively. Above this ratio, uncontrolled aggregation resulted in micrometer-sized aggregates or coacervates (Figure 2D). The loss of particle stability can be explained by a geometrical model. Assuming a homogeneous sphere with a radius of 24 nm, consisting of 214 monomers, each exposed monomer terminus occupies a surface of 33.8 nm² or a sphere with a radius of approximately 2 nm. Since the radius of VHVs is around 2–3 nm, it is highly plausible that steric hindrance at high VHH-ELPDB ratios occurs, leading to rearrangement and/or aggregation.

Incorporation of 10% VHH-ELPDB resulted in well-defined micelles with physicochemical characteristics similar to ELPDB micelles (Table 2, Figures 2C and S3). This percentage should result in a display of approximately 20 VHH molecules per micelle.

Since the LCST of ELPDB is concentration dependent, we determined the critical micelle concentration (CMC) by dynamic light scattering (DLS) and found that the CMC is lower than 100 nM (Figure S4).

In order to mimic in vivo conditions we investigated the effect of the presence of human serum (HS) on the particle properties. ELP micelles in HS were shown to be stable for at least 2 h at 37 °C and, furthermore, could be reversibly assembled in a temperature-dependent manner (Figure S5).

To separately follow the fate of VHH-ELPDB and ELPDB after cellular uptake of composite micelles, we labeled VHH-ELPDB with fluorescein-5,5'-maleimide (FL), yielding 7D12FL−ELPDB and Fc5FL−ELPDB. ELPDB was labeled with Alexa647-N-hydroxy succinimide (NHS) ester or IRDye700DX (PS) via NHS chemistry at the N-terminal amino group of ELPDB, yielding Alexa647-ELPDB and PS-ELPDB, respectively (Table 1, Figure S6).

FL-fluorescence-based flow cytometry, performed at 4 °C to prevent self-assembly into micelles and internalization, showed that monomeric 7D12FL−ELPDB, but not Fc5FL−ELPDB, effectively bound to EGFR-expressing A431 cells (Figure 3A), demonstrating that the 7D12 moiety had retained its EGFR affinity. 7D12FL−ELPDB binding was slightly less than the 7D12EC control, indicating that the fusion to ELPDB may induce some steric hindrance at low temperatures. No binding to the EGFR-negative E98 cell line was observed for either 7D12FL−ELPDB or Fc5FL−ELPDB. These experiments clearly illustrate that the specificity of 7D12 remains unchanged in the context of a fusion protein with ELPDB, and that ELPDB itself did not show aspecific binding to the cell lines tested.

We next prepared micelles by heating a mixture of ELPDB, Alexa647-ELPDB, and VHHFL-ELPDB (85:5:10) to 37 °C and analyzed in vitro binding and uptake by measuring cell-associated FL fluorescence and Alexa647 fluorescence in flow cytometry experiments. 7D12FL−Alexa647-ELPDB micelles associated with A431 cells but not with EGFR-negative E98 cells (Figure 3B).

Incubation with composite 7D12FL−Alexa647-ELPDB micelles resulted in 44% higher cell-associated FL fluorescence relative to the situation in which equal concentrations of (monomeric) 7D12FL were used, indicating a multivalency and avidity effect of 7D12FL induced by particle formation. Of note, incubation of A431 with 7D12FL−Alexa647-ELPDB micelles also resulted in cell-associated Alexa647 fluorescence (Figure 3B), and fluorescence microscopy revealed membranous and intracellular colocalization of both Alexa647 and FL (Figure S7), indicating that 7D12FL associated with the cells as part of intact micelles. Fc5FL−Alexa647-ELPDB micelles showed little background association with A431 cells. Altogether, these data show that composite 7D12FL−Alexa647-ELPDB micelles that target tumor cells in an EGFR-specific manner can be created.

Unfortunately, 7D12 binds to EGFR only in a cell context. Since the VHH is internalized upon EGFR binding at 37 °C, it is difficult to quantitatively compare avidity effects of 7D12FL in micellar or monomeric form, because at 37 °C results will always be biased by internalization effects. Future studies with other VHH-ELP constructs that can be used in cell-free systems may provide important answers on the subject of avidity.

In an effort to determine the CMC of the functionalized particles in vitro, we varied the concentration of all components, maintaining the same ratios. As shown in Figure 3C, 7D12-induced binding and uptake of Alexa647-ELPDB occurred at concentrations as low as 160 nM (VHH concentration of 16 nM), showing the presence of cofunctionalized micelles and agreeing with results obtained by DLS. Using lower ELPDB concentrations for more accurate determination of the CMC was not feasible due to insufficient fluorophore signal-to-noise ratio. For a more accurate determination in vitro, we used the photodynamic therapy assay as described below.

To test whether EGFR-targeting ELPDB-based micelles can be used in a therapeutic manner, we prepared 7D12FL−ELPDB micelles containing the photosensitizer IRDye700DX, conjugated to ELPDB (PS-ELPDB). To achieve maximum drug loading while maintaining sufficient targeting capacity, we prepared micelles containing 2% VHHFL−PS−ELPDB and 98% PS−ELPDB. Cell-killing efficiency of these micelles was compared to cell killing by monomeric 7D12, directly conjugated with IRDye700DX (7D12PS). A431 or E98 cells were incubated with 7D12PS-micelles or equimolar amounts of 7D12PS prior to illumination. 7D12FL−PS−ELPDB micelles actively killed A431 cells in a light-dependent and 7D12-specific manner with an EC50 concentration of 82.7 pM compared to 121.5 pM for the 7D12PS control (Figure 4A). This indicates that micelles were formed already at a VHH concentration as low as 82.7 pM, corresponding to an ELPDB concentration of 4.1 nM. No toxicity was observed toward E98 cells, proving that 7D12-mediated binding and uptake is necessary for toxicity. Control micelles composed of 2% Fc5FL−ELPDB and 98% PS−ELPDB showed no light-dependent toxicity upon illumination of either A431 or E98 cells. Importantly, no dark toxicity of either particle was found (Figure 4B). The cell-killing efficiency of 7D12FL−ELPDB particles preincubated in human serum at 37 °C for up to 4 h, was surprisingly increased compared to particles diluted in DMEM/10%FCS (Figure S8), indicating that particles are stable and therapeutically active in 100% serum.

The cell-specificity of the particles was further confirmed by coculturing DiO-labeled A431 (green) and DiD-labeled E98 (blue) cells and performing photoimmunotherapy as described above. By staining dead cells with propidium iodide, it was observed that only EGFR expressing A431 cells died (Figure 4C). Thus, targeted photoimmunotherapy with 7D12FL−PS−ELPDB micelles is highly specific for target-expressing cells without harming neighboring target-negative cells.

The used light dose of 60 J/cm² is physiologically relevant; clinical studies reported safe use of light doses up to 125 J/cm² in, for example, nonsmall cell carcinoma in the lung and cervical cancer. Still, the penetration depth of near-infrared light is below 1 cm, and therefore this treatment will often have to be combined with surgery.
Assuming Poisson distribution, 2% VHH-ELP<sup>DB</sup> are sufficient to ensure that ~98% of all particles contain at least one targeting moiety. This leaves ample opportunities to combine several targeting groups in one particle and to further optimize their composition.

## CONCLUSION

In conclusion, we have shown successful self-assembly of VHH-ELP<sup>DB</sup> conjugates into micelles that can be used for targeted photodynamic therapy in vitro and potentially in vivo. The 24 nm radii of these micelles are considered excellent for nanomedicine; large enough to avoid rapid clearance from the circulation, yet small enough to extravasate and penetrate the intercellular space of tumors. The system allows implementation of multiple VHHs to generate multitargeted drug delivery nanoparticles. Spontaneous micelle formation required concentrations as low as 4.1 nM. Further efforts will focus on validating the in vivo stability and activity of ELP<sup>DB</sup> nanoparticles. Combining the system with therapeutic and diagnostic molecules may result in an interesting theranostic platform.

## ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.biomac.7b00064.

Protein sequence data SEC-MALS data of ELP<sup>DB</sup> and 10% Fc5-ELP<sup>DB</sup> CMC determination by DLS particles stability in human serum, as determined by DLS mass spectrometry data for all modified proteins. Microscopy of A431 cells after incubation with VHH<sup>FL</sup>-Alexa<sup>488</sup>, ELP<sup>DB</sup> micelles. Effectivity of PIT after prior incubation in human serum (PDF).

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### Funding

This work was supported by Radboud University, Radboudumc, and the Ministry of Education, Culture and Science (Gravitation Program 024.001.035).

### Notes

The authors declare no competing financial interest.

### ACKNOWLEDGMENTS

We are grateful to A. Spies and M. van Stevendaal for preliminary work on VHH-ELP conjugates.

### ABBREVIATIONS

A431, cell line expressing EGFR; CBB, Coomassie Brilliant Blue; CMC, critical micelle concentration; DLS, dynamic light scattering; E98, cell line not expressing EGFR; EGFR, endothelial growth factor receptor; ELP, elastin-like peptide; ELP<sup>DB</sup>, elastin-like peptide diblock copolypeptide; LCST, lower critical solution temperature; PIT, photodynamic immunotherapy; PS, photosensitizer; SEC-MALS, size-exclusion chromatography multiangle light scattering; VHH, heavy-chain antibody fragments

## REFERENCES


