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NMR Solution Structure and Condition-Dependent Oligomerization of the Antimicrobial Peptide Human Defensin 5

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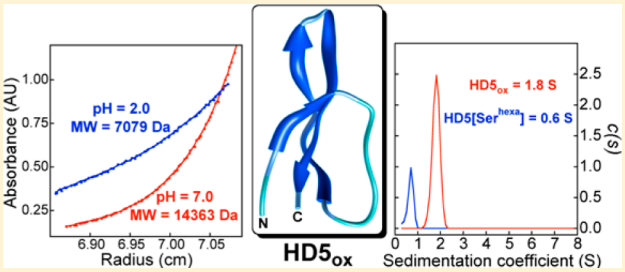
Supporting Information

ABSTRACT: Human defensin 5 (HD5) is a 32-residue host-defense peptide expressed in the gastrointestinal, reproductive, and urinary tracts that has antimicrobial activity. It exhibits six cysteine residues that are regiospecifically oxidized to form three disulfide bonds (Cys^3–Cys^{31}, Cys^5–Cys^{20}, and Cys^{10}–Cys^{30}) in the oxidized form ($HD5_{ox}$). To probe the solution structure and oligomerization properties of $HD5_{ox}$, and select mutant peptides lacking one or more disulfide bonds, NMR solution studies and analytical ultracentrifugation experiments are reported in addition to *in vitro* peptide stability assays. The NMR solution structure of $HD5_{ox}$, solved at pH 4.0 in 90:10 H_2O/D_2O, is presented (PDB: 2LXZ). Relaxation T_1/T_2 measurements and the rotational correlation time (τ_c) estimated from a ^{15}N-TRACT experiment demonstrate that $HD5_{ox}$ is dimeric under these experimental conditions. Exchange broadening of the Hα signals in the NMR spectra suggests that residues 19–21 (Val^{19}–Cys^{20}–Glu^{21}) contribute to the dimer interface in solution. Exchange broadening is also observed for residues 7–14 comprising the loop. Sedimentation velocity and equilibrium studies conducted in buffered aqueous solution reveal that the oligomerization state of $HD5_{ox}$ is pH-dependent. Sedimentation coefficients of ca. 1.8 S and a molecular weight of 14 363 Da were determined for $HD5_{ox}$ at pH 7.0, supporting a tetrameric form ($[HD5_{ox}] \geq 30$ μM). At pH 2.0, a sedimentation coefficient of ca. 1.0 S and a molecular weight of 7079 Da, corresponding to a $HD5_{ox}$ dimer, were obtained. Millimolar concentrations of NaCl, $CaCl_2$, and $MgCl_2$ have a negligible effect on the $HD5_{ox}$ sedimentation coefficients in buffered aqueous solution at neutral pH. Removal of a single disulfide bond results in a loss of peptide fold and quaternary structure. These biophysical investigations highlight the dynamic and environmentally sensitive behavior of $HD5_{ox}$ in solution, and provide important insights into $HD5_{ox}$ structure/activity relationships and the requirements for antimicrobial action.



Host-defense peptides and proteins are key players in the mammalian innate immune response and serve to prevent colonization by invading pathogenic microbes.[1−5] Human defensins are ribosomally synthesized, cysteine-rich, host-defense peptides expressed in neutrophils (human neutrophil peptides, HNPs) and various types of epithelial cells (α- and β-defensins).[6−9] Human defensin 5 (HD5), the focus of this work, is an α-defensin comprised of 32 amino acids that exhibits three regiospecific disulfide bonds with the connectivities Cys^3–Cys^{31}, Cys^5–Cys^{20}, and Cys^{10}–Cys^{30} in the oxidized form, hereafter $HD5_{ox}$ (Figure 1). Like other α-defensins, the $HD5_{ox}$ disulfide array confers a three-stranded β-sheet structure[10] and protease resistance.[11,12]

HD5 is expressed in the human gastrointestinal,[13−16] reproductive,[17] and urinary[18] tracts. Small intestinal Paneth cells,[19] which reside at the base of the crypts of Lieberkühn throughout the small intestine and serve to protect the intestinal epithelium and stem cells from invading microbes, package the HD5 propeptide in subcellular granules.[15,20] The 75-aa propeptide is converted into the 32-aa mature form by trypsin-catalyzed proteolysis of the N-terminal 43-aa pro region, and HD5 is released into the intestinal lumen in response to microbial invasion.[21] Numerous *in vitro* studies demonstrated that $HD5_{ox}$ exhibits antimicrobial activity against a variety of Gram-negative and -positive human pathogens including *Escherichia coli*, *Salmonella enterica*, *Bacillus cereus*, *Listeria monocytogenes*, *Staphylococcus aureus*, and *Enterococcus facieum*.[10,22,23] A HD5 transgenic mouse, which expresses HD5 only in the small intestinal Paneth cells, survived oral *Salmonella* challenge (1.5×10^9 cfu/mL) at levels that were lethal for the wild-type mouse.[24] This observation supports an antibacterial role for HD5 *in vivo*. Recent HD5 transgenic mouse studies of the commensal microbiota revealed that HD5

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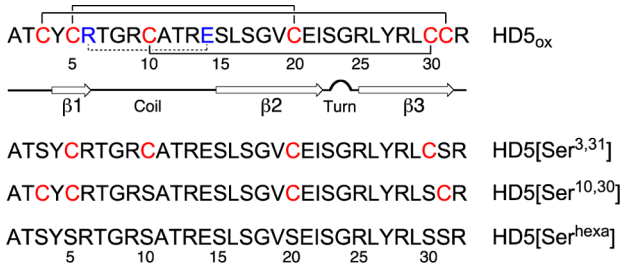

Figure 1. Primary amino acid sequences of $HD5_{ox}$ and the mutant peptides employed in this work. The numbers refer to amino acid position. The Cys residues comprising the Cys^3–Cys^{31}, Cys^5–Cys^{20}, and Cys^{10}–Cys^{30} disulfide linkages (solid lines) are shown in red and the residues of the Arg^6–Glu^{14} salt-bridge (dashed line) are indicated in blue. The secondary structure depiction is based on the NMR solution structure presented in this work. Throughout the main text, the regiospecific disulfide linkages that define each mutant peptide are indicated in parentheses.

expression modulates the composition of the resident microflora.[25] Defensin deficiency has been observed in patients with inflammatory diseases of the small bowel.[26,27] A single R13H point mutation in HD5 was observed in a Crohn's disease patient, and this mutation afforded attenuated cell killing for some bacterial species *in vitro*.[28] Indeed, an *E. coli* Nissle 1917 strain engineered to biosynthesize and secrete HD5 was recently reported as a possible probiotic therapy for Crohn's disease and other inflammatory diseases of the bowel.[29] Antiviral activities of $HD5_{ox}$ are also documented.[30−32] For instance, $HD5_{ox}$ blocks infection by various nonenveloped human viruses, including adenoviruses[31,32] and sexually transmitted papillomaviruses,[30] and may provide a natural barrier to certain viral diseases in the female reproductive system.

The broad-range antibacterial and antiviral activities of $HD5_{ox}$, in addition to other putative physiological roles, motivate investigations of structure−activity relationships. To date, these studies have addressed the importance of the arginine residues,[28] the role of the canonical salt bridge formed by Arg^6–Glu^{14},[11] and the disulfide array.[12,33] The antibacterial activity of the D-enantiomer, prepared by solid-phase peptide synthesis, was also evaluated and exhibited species-specific activity.[34] A recent alanine scan identified Leu^{27} as a critical determinant for antibacterial activity.[35] Taken together, these investigations overwhelmingly support a model whereby the mechanism of $HD5_{ox}$ action differs for Gram-negative (e.g., *E. coli*) and -positive (e.g., *S. aureus*) organisms. Whereas a variety of HD5 mutant peptides, including the D-enantiomer and disulfide deletion mutants, retain activity against *E. coli*, the ability of these peptides to kill *S. aureus* is severely attenuated.[12,33,34] $HD5_{ox}$ disrupts the Gram-negative inner membrane;[12] however, the precise details of its mechanism of action against *E. coli* and other Gram-negative organisms, in addition to how it acts on Gram-positive species, are unclear. Extensive mutagenesis studies of the human neutrophil α-defensin HNP1[36−40] and the murine Paneth cell α-defensin cryptdin-4 (Crp4)[41−46] have been presented. In total, these studies delineate that defensin structure/activity relationships must be considered on a case-by-case basis, and highlight the importance of evaluating both electrostatics and hydrophobicity when considering the antimicrobial and antiviral activities of human α-defensin peptides.[4]

We previously reported a $HD5_{ox}$ mutant peptide family in which pairs of Cys residues involved in native disulfide linkages were systematically mutated to Ser/Ala residues.[12] Many of these mutants retained antibacterial activity against *E. coli* ATCC 25922, whereas none provided activity against *S. aureus* ATCC 25923 over the concentration range tested. In addition, removal of one or more disulfide bonds markedly attenuated protease resistance. We therefore hypothesized that the lack of antibacterial activity observed for the mutant peptides against *S. aureus* may result from (i) mutant peptide instability under the assay conditions, (ii) disruption of quaternary structure, and/or (iii) failure to interact with a specific and as-yet unidentified cellular target.

Herein we address these possibilities and report extensive biophysical studies designed to probe the solution structure and dynamics of $HD5_{ox}$ and select disulfide mutant peptides (Figure 1). We present the NMR solution structure of native $HD5_{ox}$ in addition to NMR studies of ^{15}N-$HD5[Ser^{3,31}]_{ox}$, ^{15}N-$HD5[Ser^{10,30}]_{ox}$, and ^{15}N-$HD5_{red}$. We also describe the quaternary structure of $HD5_{ox}$ and disulfide mutants by using a combination of NMR dynamics measurements, rotation correlation time measurements, and analytical ultracentrifugation. These investigations demonstrate that the native disulfide array is essential for $HD5_{ox}$ quaternary structure, and that the $HD5_{ox}$ oligomerization state in aqueous solution is condition-dependent.

EXPERIMENTAL PROCEDURES

Materials and General Methods. All solvents, reagents, and chemicals were purchased from commercial suppliers and used as received unless noted otherwise. Deuterated water (D_2O), ^{15}N-ammonium chloride, and U-^{13}C-glucose were purchased from Cambridge Isotopes (Cambridge, MA). All aqueous solutions, buffers, and NMR samples were prepared with Milli-Q water (18.2 mΩ cm^{-1}) that was passed through a 0.22-μm filter before use. Unlabeled HD5 and mutant peptides were overexpressed as His_6-fusion proteins in *E. coli* BL21(DE3) and were purified as previously described.[12]

General Instrumentation. Analytical and semipreparative high-performance liquid chromatography (HPLC) were performed on an Agilent 1200 instrument equipped with a thermostatted autosampler set at 4 °C and thermostatted column compartment generally set at 20 °C, and a multiwavelength detector set at 220 and 280 nm (500 nm reference wavelength unless noted otherwise). Preparative HPLC was performed using an Agilent PrepStar 218 instrument outfitted with an Agilent ProStar 325 UV−vis dual-wavelength detector set at 220 and 280 nm. A Clipeus C18 column (5 μm pore, 4.6 × 250 mm, Higgins Analytical, Inc.) set at a flow rate of 1 mL/min was employed for all analytical HPLC experiments. A ZORBAX C18 column (5 μm pore, 4.6 × 250 mm, Agilent Technologies, Inc.) set at a flow rate of 5 mL/min was employed for all semipreparative-scale HPLC purification. A Luna 100 Å C18 LC column (10 μm pore, 21.2 × 250 mm, Phenomenex) operated at 10 mL/min was utilized for all preparative-scale HPLC purification. HPLC-grade acetonitrile (MeCN) and HPLC-grade trifluoroacetic acid (TFA) were routinely purchased from EMD. For all HPLC separations, solvent A was 0.1% TFA/H_2O and solvent B was 0.1% TFA/MeCN. These solvents were passed through a 0.22-μm filter prior to use. High-resolution mass spectrometry was performed by using an Agilent LC/MS system comprised of an Agilent 1260 series LC system outfitted with an Agilent Poroshell 120 EC-C18 column (2.7 μm pore size) and an Agilent 6230 TOF system housing an Agilent Jetstream ESI source. LC/MS-grade

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MeCN containing 0.1% formic acid and LC/MS-grade water containing 0.1% formic acid were obtained from J. T. Baker. For all LC/MS analyses, solvent A was 0.1% formic acid/H_2O and solvent B was 0.1% formic acid/MeCN. The samples were analyzed by using a gradient of 5−95% B over 5 min with a flow rate of 0.4 mL/min. The MS profiles were analyzed and deconvoluted by using Agilent Technologies Quantitative Analysis 2009 software version B.03.02. A BioTek Synergy HT plate reader outfitted with a calibrated BioTek Take3 Multi-Volume Plate was employed for optical absorption measurements. Peptide stock solution concentrations were routinely quantified by using the calculated extinction coefficients for $HD5_{ox}$ or mutant peptide (Table S1, Supporting Information). Solution and buffer pH values were verified by using either a Mettler Toledo S20 SevenEasy pH meter or a HANNA Instruments HI 9124 pH meter equipped with a microelectrode.

Overexpression and Purification of ^{15}N and $^{13}C,^{15}N$-Labeled Peptides. The plasmids employed for the overexpression of His_6-Met-HD5, His_6-Met-HD5[$Ser^{3,31}$], and His_6-Met-HD5[$Ser^{10,30}$] are based on the pET-28b expression vector and are described elsewhere.[12] Each expression plasmid was transformed into homemade chemically competent *E. coli* BL21(DE3) cells and freezer stocks were prepared from single colonies. For large-scale overexpression of ^{15}N-labeled peptides, a 50-mL overnight culture was prepared by inoculating LB media containing 50 μg/mL kanamycin from a freezer-stock of the desired *E. coli* overexpression strain. The starter culture was grown for 16 h (37 °C, 175 rpm) and the OD_{600} was recorded to confirm that the cultures reached saturation (OD_{600} ∼ 1.5). Aliquots (20 mL) of the overnight culture were centrifuged (3600 rpm × 10 min, 4 °C) and the supernatant was discarded. Each resulting cell pellet was resuspended in 3 mL of sterile-filtered ^{15}N-labeled M9 minimal medium (6.0 g/L disodium phosphate, 3.0 g/L monopotassium phosphate, 0.5 g/L sodium chloride, 1.0 g/L ^{15}N-labeled ammonium chloride) supplemented with 2 mL/L of 1 M $MgSO_4$, 2 mL/L of 5 mM $FeCl_3$, 100 μL/L of 1 M $CaCl_2$, 1 mL/L of glycerol, 2.0 g/L of D-glucose, 1 mL/L of 50 mg/mL kanamycin, and 200 μL of a vitamin mix.[47] The vitamin mix contained choline chloride (200 mg), folic acid (250 mg), pantothenic acid (250 mg), nicotinamide (250 mg), myo-inositol (50 mg), pyridoxal hydrochloride (250 mg), thiamin hydrochloride (250 mg), riboflavin (25 mg), adenosine (50 mg), and biotin (50 mg) suspended in 7.5 mL of sterile-filtered Milli-Q water. Each resuspended bacterial cell pellet was used to inoculate 1 L of the same minimal medium, and the resulting cultures were grown at 37 °C with shaking at 175 rpm in 4 L baffled flasks. Protein expression was induced by addition of IPTG (0.5 mL of a 0.5 M aqueous stock solution, 250 μM final concentration) at OD_{600} ∼ 0.6 (t ∼ 5.5 h). The cultures were incubated at 37 °C with shaking at 175 rpm for an additional 5.5 h, and the cells were immediately pelleted by centrifugation (4000 rpm × 30 min, 4 °C). ^{15}N-Labeled $HD5_{ox}$ was overexpressed on a 4-L scale and the ^{15}N-labeled mutant peptides were each overexpressed on a 12-L scale. The final OD_{600} values varied from ca. 0.7 to ca. 1.2 depending on the shaker flask. The resulting cell pellets were collected, flash frozen in liquid N_2, and stored at −80 °C. The wet pellet yield for ^{15}N-His_6-Met-HD5 was ca. 2 g/L culture. Wet pellet yields of ca. 1.2 and ca. 1.8 g/L culture were obtained for ^{15}N-His_6-Met-HD5[$Ser^{3,31}$] and ^{15}N-His_6-HD5[$Ser^{10,30}$], respectively. Overexpression of double-labeled $^{13}C,^{15}N$-His_6-Met-HD5 was performed on a 6-L scale by using the same method and substituting U-^{13}C-glucose for unlabeled glucose.

Isotopically-labeled His_6-HD5 and the His-tagged mutant peptides were purified as described previously for the unlabeled congeners.[12] In brief, the His_6-tagged HD5 and serine double mutants were isolated in yields of ca. 5−15 mg/L culture following Ni-NTA affinity chromatography. Each His_6 tag was cleaved by using cyanogen bromide, and each crude peptide was reduced by addition of TCEP and HPLC purified. An oxidative folding procedure was employed to obtain the oxidized forms, which were separated and purified by semipreparative HPLC.[12] Peptide purity was ascertained by analytical HPLC (Figures S1−S4), and peptide identities were confirmed by mass spectrometry (Table S2). The purified peptides were lyophilized to dryness and stored as powders at −20 °C until use. Some disulfide bond shuffling was observed by analytical HPLC for several unlabeled disulfide deletion mutants after several months of storage at −20 °C in neutral aqueous solution. As a result, the ^{15}N-labeled disulfide regioisomers of the serine double mutants were stored as lyophilized powders until use.

Peptide Stability in the Presence of *Staphylococcus aureus*. *S. aureus* ATCC 25923 was grown overnight with shaking (37 °C, 16 h) in 5 mL of TSB. The overnight culture was diluted 1:100 into 6 mL of fresh TSB and grown for ∼2 h at 37 °C with shaking at 150 rpm until the OD_{650} reached ∼0.6. A 5-mL portion of the culture was transferred to a sterile culture tube and centrifuged (3500 rpm × 10 min, 4 °C) to pellet the bacterial cells. The supernatant was discarded and the cell pellet was resuspended in 5 mL of AMA buffer (10 mM sodium phosphate buffer supplemented with 1% TSB, pH 7.4). The cell suspension was centrifuged (3500 rpm × 10 min, 4 °C) and the supernatant was discarded. The resulting cell pellet was resuspended in 5 mL of AMA buffer and diluted with AMA buffer to obtain an OD_{650} value of 0.6 (1×10^8 CFU/mL). This bacterial suspension was further diluted 1:100 in two steps (1:10 × 1:10) into 2 mL of AMA buffer. The diluted cultures were used immediately.

Peptide stability assays were performed in 96-well plates. Each well contained 10 μL of a 200-μM (10×) aqueous sterile-filtered peptide stock solution or a no-peptide control. A 90-μL aliquot of the diluted bacterial culture was added to each well and the plate was incubated for 1 h (37 °C, 150 rpm). Wells containing AMA buffer only and peptide in the AMA buffer without *S. aureus* were also included. Immediately after the 1-h incubation, each culture was transferred to a microcentrifuge tube and the samples were centrifuged (13 000 rpm × 10 min, 4 °C). The supernatants were transferred to new microcentrifuge tubes, a 10-μL aliquot of 2% aqueous TFA was added to each solution, and the samples were centrifuged (13 000 rpm × 10 min, 4 °C). The resulting supernatants were transferred to HPLC vials and stored in an autosampler thermostatted at 4 °C until analytical HPLC analysis (10−60% B over 30 min). This assay was conducted at least in triplicate for each peptide and over two separate days. Representative HPLC traces are reported in Figures 2 and S5−S6.

Solution NMR Sample Preparation. Samples of ^{15}N-$HD5_{ox}$ were prepared at different concentrations and pH values to determine the optimal sample conditions for NMR data collection. Initial data acquisition was performed on a 460-μM sample of ^{15}N-$HD5_{ox}$ that was dissolved in 90:10 H_2O/D_2O immediately after HPLC purification and lyophilization (Figure 3). Additional samples of ^{15}N-$HD5_{ox}$ were prepared at pH 5.0

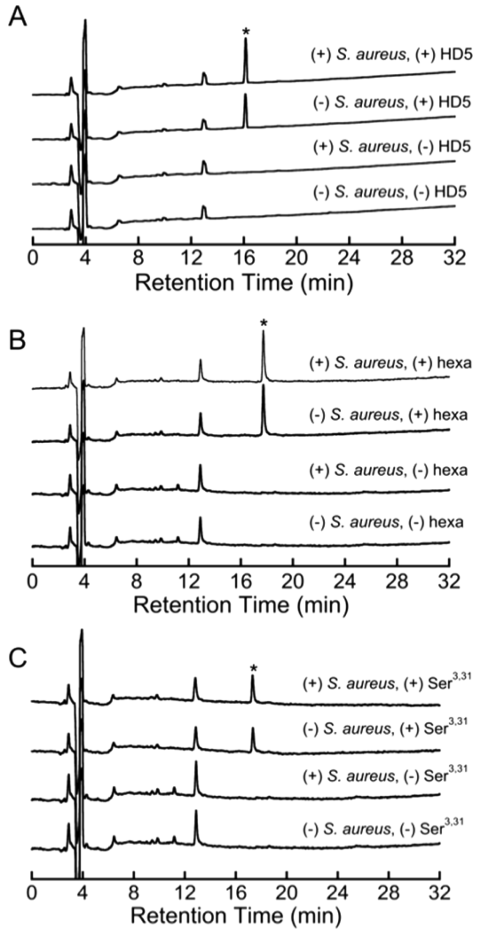

Figure 2. Analytical HPLC traces of *S. aureus* culture supernatants (10 mM sodium phosphate buffer supplemented with 1% TSB, pH 7.4) treated with 20 μM of $HD5_{ox}$ or a mutant peptide for 1 h at 37 °C. (A) $HD5_{ox}$. (B) $HD5[Ser^{hexa}]$. (C) $HD5[Ser^{3,31}]$ (5−10)(20−30). Absorption at 220 nm was monitored with a reference wavelength of 500 (A) or 360 nm (B and C) (10−60% B in 30 min). In each panel, the star indicates the peak corresponding to the defensin peptide. Traces for other HD5 mutants are provided as Supporting Information.

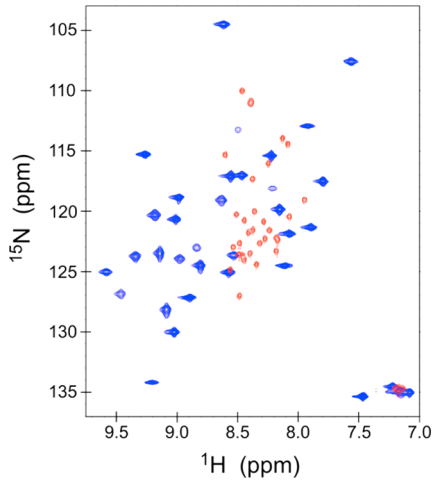

Figure 3. Overlay of ^{15}N-$HD5_{ox}$ (blue) and ^{15}N-$HD5_{red}$ (red) $^{1}H,^{15}N$-HSQC spectra recorded on a 600 MHz spectrometer. The concentration of $HD5_{red}$ was 650 μM, and the sample was prepared in 90:10 H_2O/D_2O containing 20 μM TFA. The $HD5_{ox}$ sample concentration was 460 μM, and the sample was prepared in 90:10 H_2O/D_2O immediately after HPLC purification and lyophilization, and no pH adjustment was performed.

(630, 460, and 260 μM) by using an aqueous solution of 1 N HCl for adjusting the sample pH. In a separate screen, ^{15}N-$HD5_{ox}$ samples at pH 7.0 (333 μM), 6.0 (340 μM), 5.0 (400 μM), and 4.0 (460 μM) in 90:10 H_2O/D_2O were prepared by using TFA to adjust pH as necessary. To determine the effect of buffer, samples of ^{15}N-$HD5_{ox}$ (800 μM) were prepared in 20 mM Tris-HCl buffer containing 10% D_2O (v/v) at pH = 7.0, 6.0, and 5.0. Lastly, ^{15}N-$HD5_{ox}$ (880 μM) was prepared in 10 mM sodium phosphate buffer with 10% D_2O (v/v) at pH = 7.0, 6.0, and 4.0. In these two sets of samples, the sample pH was adjusted by incremental additions of 1 N HCl. On the basis of the $^{1}H,^{15}N$-HSQC spectra of ^{15}N-$HD5_{ox}$ prepared under various conditions, the $^{13}C,^{15}N$-$HD5_{ox}$ sample (340 μM) was prepared in 90:10 H_2O/D_2O at pH 4.0, and TFA was employed to adjust the sample pH. These conditions afforded the greatest peak dispersion, and 28 of 31 amide resonances were observed for $^{13}C,^{15}N$-$HD5_{ox}$ in the $^{1}H,^{15}N$-HSQC spectrum. Likewise, all ^{15}N-$HD5[Ser^{3,31}]_{ox}$ and ^{15}N-$HD5[Ser^{10,30}]_{ox}$ regioisomers were prepared in 90:10 H_2O/D_2O at pH 4.0. The NMR sample of ^{15}N-$HD5_{red}$ (650 μM) was prepared in 90:10 H_2O/D_2O containing 20 μM TFA to ensure that the peptide remained reduced.

Solution NMR Spectroscopic Studies. All 1-D ^{1}H NMR spectra were collected on a Varian 500 MHz spectrometer housed in the MIT Department of Chemistry Instrumentation Facility (DCIF) that was operated at an ambient probe temperature of 293 K (Figures S7 and S8). Standard techniques for water suppression and data acquisition were employed. A number of multidimensional NMR spectra were recorded on a 600 MHz NMR spectrometer housed in the MIT Francis Bitter Magnet Laboratory (FMBL) based on a FBML narrow bore magnet and a console designed and constructed by members of the FBML. This spectrometer is equipped with three transmitter channels, and a Nalorac 5 mm indirect triple resonance $^{1}H[^{13}C,^{15}N]$ probe with z-gradient. Additional multidimensional NMR spectra were recorded on a 600 MHz Bruker Avance spectrometer equipped with a cryogenic probe housed at Harvard Medical School. To determine optimal acquisition conditions for $HD5_{ox}$, $^{1}H,^{15}N$-HSQC experiments were performed at 15, 20, and 25 °C. For the initial resonance assignments, TOCSY and NOESY experiments were performed at 25 °C. 2-D TOCSY spectra were recorded with mixing times of 30 and 60 ms, and 2-D NOESY spectra were recorded with mixing times of 150, 200, and 400 ms. All experiments were acquired with 2048 complex points in t_2 and 512 complex points in t_1, and a sweep width of 12 ppm in both dimensions. The 3-D ^{15}N-edited TOCSY and 3-D ^{15}N-edited NOESY experiments were collected with 60 and 200 ms mixing times, respectively. A 200 ms mixing time was also employed for a 3-D ^{13}C-edited NOESY experiment. Sequence-specific assignment was aided by the collection of standard HNCA, HNCO, and HNCACO pulse sequences; however, nonuniform sampling was used. Specifically, a matrix of 38 points (^{15}N dimension) by 40 points (^{13}C dimension) at the ca. 20% level (a total of 320 acquired complex points) was subsampled. The sampling schedule was created based on the Poisson Gap sampling method.[48] Missing data points were reconstructed by using the istHMS algorithm.[49] Only 1-D ^{1}H NMR and 2-D

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$^{1}H,^{15}N$-HSQC spectra for the HD5[$Ser^{3,31}$]$_{ox}$ and HD5-[$Ser^{10,30}$]$_{ox}$ regioisomers were collected, and the HSQC experiments were conducted over a temperature range of 15−25 °C. Spectral data were processed by using NMRPipe[50] and analyzed by using Sparky[51] or CARA.[52]

NMR Solution Structure Calculations and Refinement. Structure calculations were initially performed in CYANA to fully assign NOE crosspeaks and establish the hydrogen bond network by inference from preliminary structures along with NOE patterns. These NOE assignments were then used in structure calculations with X-PLOR NIH using explicit water refinement. During this calculation, the system was cooled from 3000 to 25 K within 10 ps, applying the high force constants obtained at the end of the previous cooling stage. The experimental restraints included 421 upper distance limits, 54 dihedral angles identified by analysis of backbone chemical shifts by the program TALOS,[53] 16 χ_1 angles, 3 disulfide bonds, and 15 hydrogen bonds.

Of the 400 structures resulting from the final round of structure calculation, the 20 lowest-energy structures were selected. The geometry and elements of secondary structure were analyzed using PROCHECK.[54] These coordinates are deposited in the Protein Data Bank (code: 2LXZ). The UCSF Chimera[55] package and MOLMOL[56] were employed for final graphical presentation.

Sedimentation Velocity Experiments. A Beckman XL-I Analytical ultracentrifuge outfitted with an An-50 Ti rotor was employed for all sedimentation velocity (SV) experiments. The rotor housed conventional double-sector charcoal-filled Epon centerpieces within the sample cells and contained either sapphire (Rayleigh interference optics) or quartz (absorption optics) windows. The absorption wavelength for optical detection was 280 nm, and the interferometer laser wavelength was 660 nm. The samples were centrifuged at 42 000 rpm and 20 °C until sedimentation was complete. SEDNTERP[57] was employed to calculate the buffer viscosity (η), buffer density (ρ), and protein partial specific volume ($\bar{v}$) values at 20 °C based on a database of known values available via the Internet (http://www.jphilo.mailway.com). The sedimentation coefficients were subsequently calculated by fitting the sedimentation velocity data using SEDFIT. The continuous distribution $c(s)$ Lamm equation model, which accounts for protein diffusion, was employed.[58] The sedimentation coefficients generated by this approach were confirmed by using DCDT+.[59,60] The apparent sedimentation coefficient distribution, $g(s^*)$, was generated from 22 to 26 scans with a peak broadening limit of 60 kDa using DCDT+.

All SV window assemblies were loaded with 410 μL of buffer reference and 400 μL of peptide sample, and the buffers and samples were prepared immediately before the SV runs. In one set of experiments, samples of $HD5_{ox}$, the HD5[$Ser^{3,31}$]$_{ox}$ and HD5[$Ser^{10,30}$]$_{ox}$ regioisomers, and HD5[Ser^{hexa}] were prepared at pH 7.0 in 10 mM sodium phosphate buffer. A solution of 1 N HCl was employed to adjust pH. Starting from a lyophilized peptide sample, a concentrated stock solution of each peptide was prepared from buffer that was filtered through a 0.45-μm membrane. In microcentrifuge tubes, aliquots of the peptide stock solution were diluted to 400 μL with buffer to provide the desired concentrations and subsequently transferred to the AUC sample cells. Samples at the following peptide concentrations were prepared and analyzed: $HD5_{ox}$, 30, 50, 80, 115, 120, 183, 186, 283, 301, 303, 424, and 437 μM; HD5[$Ser^{3,31}$]$_{ox}$ (5−20)(10−30), 60, 62, 65, 90, and 131 μM; HD5[$Ser^{3,31}$]$_{ox}$ (5−30)(10−20), 105, 136, and 201 μM; HD5[$Ser^{3,31}$]$_{ox}$ (5−10)(20−30), 74, 105, 153, and 210 μM; HD5[$Ser^{10,30}$]$_{ox}$ (3−20)(5−31), 153, 180, 224, and 236 μM; HD5[$Ser^{10,30}$]$_{ox}$ (3−31)(5−20), 57, 232, and 396 μM; HD5[Ser^{hexa}], 90 and 91 μM.

Additional SV experiments were conducted to evaluate the consequences of pH, salt, and buffer components on the sedimentation of $HD5_{ox}$. In all cases, the 400-μL solutions were prepared as described above and the buffer pH was adjusted by using 1 N HCl. To determine the effect of pH, samples of $HD5_{ox}$ in 10 mM sodium phosphate buffer were adjusted to pH values of 6.0 (161 μM), 4.0 (131 μM), and 2.0 (194 μM). To ascertain the effect of NaCl, samples of $HD5_{ox}$ at pH 7.0 in 10 mM sodium phosphate buffer containing 50 mM (183, 283 μM), 150 mM (181, 278 μM), and 500 mM (178, 270 μM) NaCl were prepared. To evaluate the effects of buffer choice and divalent cations, sedimentation of $HD5_{ox}$ was investigated at pH 7.0 in 20 mM Tris-HCl or 20 mM HEPES buffer with or without 50 mM $MgCl_2$ or $CaCl_2$. For the experiments in Tris buffer, the $HD5_{ox}$ concentrations were 126 and 210 μM (no divalent cations), 170 and 236 μM (+Mg), or 128 and 157 μM (+Ca). For the experiments in HEPES buffer, the $HD5_{ox}$ concentrations were 191 and 256 μM (no divalent cations), 131 and 190 μM (+Mg), and 191 and 212 μM (+Ca).

Hydrodynamic modeling computations were performed with HYDROPRO[61] to calculate sedimentation coefficients for the $HD5_{ox}$ monomer, dimer, and tetramer (Table S3). Both the $HD5_{ox}$ monomer NMR solution structure presented in this work and the reported $HD5_{ox}$ crystal structure (PDB: 1ZMP)[10] were employed in hydrodynamic modeling. All HYDROPRO calculations used the buffer density (ρ) and buffer viscosity (η) values for water at 20 °C, and a partial specific volume ($\bar{v}$) of 0.7094 mL/g for $HD5_{ox}$. Equation 1 was employed to calculate sedimentation coefficients for $HD5_{ox}$ modeled as a smooth, compact, and spherical peptide in water at 20 °C using the classical combination of the Svedberg and Stokes equation.[58] The values are reported in Table S4. Equation 1 states

$$s_{sphere} = 0.012\frac{M^{2/3}(1 - \bar{v}\rho)}{\bar{v}^{1/3}} \quad (1)$$

where s_{sphere} is the sedimentation coefficient for an ideally sedimenting sphere in S units, M is the molar mass of the macromolecule in Daltons, $\bar{v}$ is in milliliters per gram, and ρ is in grams per milliliter. To ascertain the maximum shape asymmetry from a sphere, the minimum frictional ratios were calculated with Equation 2

$$s_{sphere}/s_{20,w} = f/f_0 \quad (2)$$

where $s_{20,w}$ is the sedimentation coefficient for the peptide in water at 20 °C, f is the experimental frictional coefficient, and f_0 is the minimal frictional coefficient. The maximum shape asymmetry was determined for $HD5_{ox}$ in different buffers, HD5[Ser^{hexa}], HD5[$Ser^{3,31}$]$_{ox}$ and HD5[$Ser^{10,30}$]$_{ox}$. Each f/f_0 analysis for the disulfide deletion mutants was performed by using the average $s_{20,w}$ value determined from all regioisomeric disulfide pairings (Table S5).

Sedimentation Equilibrium Experiments. The Beckman XL-I Analytical ultracentrifuge outfitted with an An-50 Ti rotor described above was employed for all sedimentation equilibrium (SE) experiments. The absorption wavelength for optical detection was 280 nm, and the instrument was maintained at 20 °C. Samples (400 μL) of $HD5_{ox}$ were prepared in 10 mM

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sodium phosphate buffer at pH 8.0 (183, 230, and 283 μM), 7.0 (165, 187, 225, 238, 283, and 288 μM), 6.0 (210 and 330 μM), 4.0 (236, and 288 μM), and 2.0 (189, 238, and 293 μM) as described above. Equilibrium profiles were established at rotor speeds of 20 000, 25 000, and 36 000 rpm based on sedimentation coefficients of ~1.8 S obtained from the SV experiments.[62] Upon equilibrium establishment, 10 scans with 5 replicates were recorded.

SEDNTERP[57] was employed to calculate the buffer viscosity (η), buffer density (ρ), and protein partial specific volume ($\bar{v}$) values at 20 °C as described above. Molecular weights were determined by global fitting of the multispeed equilibrium data across at all loading concentrations at a given pH value using the program SEDPHAT.[63] The Species Analysis model and Single Species of an Interacting System model, both with mass conservation, were employed for data analysis with the bottom of the sample sector assigned as a floating parameter. To further verify whether each least-squares curve-fitting procedure converged to a global minimum, the alternate methods of Simplex, Marquardt−Levenberg, and simulated annealing were employed to assess any change in the global reduced chi-squared value.

RESULTS

Peptide Stability in the Presence of *S. aureus*. Figure 2 presents the analytical HPLC traces obtained for supernatants of *S. aureus* cultures treated with $HD5_{ox}$, HD5[$Ser^{3,31}$] (5−10)(20−30), and HD5[Ser^{hexa}]. Traces for additional mutants are provided as Supporting Information (Figures S5 and S6). In all cases, the peak corresponding to the peptide of interest exhibited comparable intensity whether or not *S. aureus* was included in the well. No new peaks in the analytical HPLC traces attributable to peptide degradation formed. These observations demonstrate that $HD5_{ox}$ and the disulfide mutant peptides are stable under the conditions previously employed for assaying antibacterial activity against *S. aureus*.[12] The attenuated activity of the mutant peptides reported previously results from neither peptide degradation nor disulfide bond reshuffling to an inactive form during the course of the assay.[12]

Overexpression and Purification of Isotopically-labeled Peptides. ^{15}N- and $^{13}C,^{15}N$-labeled $HD5_{ox}$ were obtained in yields of ca. 100 μg/L culture following overexpression of His_6 fusion proteins in M9 minimal media containing a vitamin supplement, Ni-NTA purification, His_6 tag cleavage, purification of the reduced form, and oxidative folding. This procedure was extended to the HD5[$Ser^{3,31}$]$_{ox}$ and HD5[$Ser^{10,30}$]$_{ox}$ peptides, which were obtained in yields of ca. 100 and ca. 300 μg/L, respectively. All isotopically labeled peptides were obtained in high purity (Figures S1−S4), and the identities were confirmed by mass spectrometry (Table S2). Although adequate for NMR studies, these yields are lower than the yields reported for peptide overexpression in nutrient-rich medium.[12] This decreased yield is largely attributed to variability in culture growth, ascertained by OD_{600} values, in minimal media. In several instances, the OD_{600} value remained ≤0.7 following induction and continued incubation at 37 °C. This phenomenon was unpredictable, and we therefore collected the cell pellets ca. 5.5 h after induction and independent of OD_{600} value at that time point. The HD5[$Ser^{5,20}$] peptides were not considered in this work because low yields of the unlabeled His-tagged peptides were achieved previously in nutrient-rich medium.[12]

NMR Solution Structure Determination of $HD5_{ox}$. A preliminary $^{1}H,^{15}N$-HSQC spectrum of ^{15}N-$HD5_{ox}$ in 90:10 H_2O/D_2O revealed 31 well-resolved amide resonances, which supported the presence of one folded species in solution (Figure 3). In contrast, markedly decreased peak dispersion was observed for ^{15}N-$HD5_{red}$ in 90:10 H_2O/D_2O containing 20 μM TFA (Figure 3), indicating that $HD5_{red}$ is unfolded. The loss of fold upon peptide reduction is in agreement with prior circular dichroism studies of HD5,[12] and a qualitative comparison of the $^{1}H,^{15}N$-HSQC spectra of oxidized and reduced human β-defensin 1.[64] Screenings of sample conditions and acquisition parameters to delineate the optimal conditions for data collection and solution structure determination were subsequently conducted. The $^{1}H,^{15}N$-HSQC spectra obtained for ^{15}N-$HD5_{ox}$ prepared in Tris or sodium phosphate buffer over the pH range of 5−7 were markedly different than the spectra of the unbuffered sample presented in Figure 3. Specifically, peaks were broader, less dispersed, and more heterogeneous in intensity for the buffered samples (Figures S9 and S10). Differences in the $^{1}H,^{15}N$-HSQC spectra were also observed for unbuffered ^{15}N-$HD5_{ox}$ prepared in 90:10 H_2O/D_2O that was pH adjusted with HCl or TFA (Figures S11−S13). Variations in acquisition temperature and sample concentration had negligible impact on chemical shift dispersion over the evaluated ranges (Figure S12). These exploratory studies highlighted the importance of sample preparation on dynamic exchange events, and further spectroscopic experiments were conducted in 90:10 H_2O/D_2O with the sample pH adjusted to 4.0 by TFA addition.

2-D homonuclear NOESY and TOCSY spectra were employed for initial ^{15}N-$HD5_{ox}$ sequence-specific assignments, using the established methods of Wüthrich.[65] These spectra where insufficient to complete sequence-specific assignment because of significant attenuation of many backbone amide signals and poor NOE data, which were most likely the results of exchange broadening. Only ca. 50% of the molecule could be assigned by using this approach, and with low confidence. A sample of $^{13}C,^{15}N$-$HD5_{ox}$ was therefore prepared, and standard triple-resonance spectra (HNCO, HNCA, HNCACO) were collected to aid in backbone assignment. In addition, 3-D ^{13}C-edited and 3-D ^{15}N-edited NOESY spectra of $^{13}C,^{15}N$-$HD5_{ox}$ were recorded. These spectra, together with the homonuclear experiments, permitted almost complete sequence-specific assignment of the $HD5_{ox}$ backbone (87.5% of the backbone assigned) and an overall assignment of 89.7% for the entire molecule (Figure S14). This assignment was sufficient for structure determination. Further assignment was hampered by exchange broadening of signals (Figure S15, *vide infra*). Additionally, backbone chemical shift assignment of the heavy nuclei provided information on backbone dihedral angles. Preliminary CYANA structure calculations confirmed beta-sheet elements, and the H-bonding network was established by the proximity of interresidue NOEs. Previous crystallographic studies of synthetic $HD5_{ox}$ revealed the α-defensin disulfide bonding pattern of Cys^3−Cys^{31}, Cys^5−Cys^{20}, and Cys^{10}−Cys^{30}.[10] In this work, characteristic intercysteine NOEs were observed between these pairs of cysteine residues (Table S6, Figure S16). Moreover, initial structure calculations were consistent with this arrangement of the disulfide bonds without explicitly declaring them in the calculation. Covalent disulfide bonding restraints for Cys^3−Cys^{31}, Cys^5−Cys^{20}, and Cys^{10}−Cys^{30} were therefore included in the final structure calculations (Figure S17). The final collection of 20 lowest-energy

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Table 1. Structure Statistics for the Solution Structure of $HD5_{ox}$

	<SA>	$(\overline{SA})_r$
r.m.s. deviations from NOE restraints (Å)[a]		
all (421)	0.032 ± 0.003	0.056
sequential [$\lvert i-j \rvert = 1$] (151)	0.035 ± 0.004	0.052
medium range [$\lvert i-j \rvert \leq 4$] (53)	0.027 ± 0.005	0.074
long-range [$\lvert i-j \rvert \geq 5$] (133)	0.024 ± 0.006	0.066
intraresidue (84)	0.035 ± 0.008	0.045
r.m.s. deviations from dihedral angles restraints (°)[b]	0.044 ± 0.017	0.877
Deviation from idealized covalent geometry		
bonds (Å)	0.011 ± 0.006	0.004
angles (°)	0.573 ± 0.081	0.523
impropers (°)	0.250 ± 0.073	0.493
Ramachandran results (%)[c]		
most favorable region	85.6 ± 3.8	92.6
additionally allowed region	14.4 ± 3.8	7.4
generously allowed region	0.0 ± 0.0	0.0
disallowed region	0.0 ± 0.0	0.0
Coordinate precision (Å)[d,e]		
protein backbone	0.135 ± 0.034	
protein heavy atoms	0.806 ± 0.102	

[a]None of the structures exhibited distance violations greater than 0.5 Å or dihedral angle violations greater than 5°. [b]The experimental dihedral angle restraints were as follows: 26 ϕ, 25 ψ, and 15 χ_1 angular restraints. [c]Determined using the program PROCHECK.[54] [d]The coordinate precision is defined as the average atomic root-mean-square deviation (RMSD) of the 20 individual SA structures and their mean coordinates. Backbone atoms are N, Cα, and C′. [e]Structure calculations also included 15 hydrogen bonds. These bonds were included in X-PLOR structure calculations as HBDB terms as described in ref 81.

structures was generated with explicit water refinement, which provided a backbone RMSD of 0.135 Å for the heavy atom backbone over the full length of the peptide (Table 1). The solution structure was determined for the $HD5_{ox}$ monomer because intermolecular NOEs were not reliably observed. The lack of intermolecular NOEs most likely results from exchange broadening of the Hα signals at the dimer interface (*vide infra*).

The overall fold of $HD5_{ox}$ exhibits a three-stranded beta-sheet characteristic of α-defensins (Figure 4). Strand β1 consists of residues 4−6, β2 is comprised of residues 15−22, and β3 extends from residues 25−31. Strands β2 and β3 are connected by a tight beta type-I turn defined by Ser^{23}-Gly^{24} (Figures 1 and 4). The three beta-sheets constitute 65% of the tertiary structure (Figure S18). This beta-sheet content is greater than that observed for Crp4 (34%)[43] and similar to the beta-sheet content (60%) of HNP3.[66] Residues 7−14 form a loop of irregularly structured secondary structure. The presence of the Arg^6−Glu^{14} salt bridge is apparent from observed NOE interactions with neighboring residues. The five additional Arg residues are positioned on one face of the structure, and on the opposite side of the predominantly hydrophobic Ser^{15}-Ile^{22} β-sheet (Figures 4C and S19). This clustering of hydrophobic and hydrophilic residues provides amphipathic character.

NMR Solution Studies of $HD5_{ox}$ Quaternary Structure and Dynamics. Evaluation of the oligomerization state of the $^{13}C,^{15}N$-$HD5_{ox}$ NMR sample was evaluated through T_1/T_2 data, a ^{15}N-TRACT experiment, and calculations of rotational correlation time (τ_c). T_1 values were measured using the standard inversion-recovery method, and T_2 data were obtained

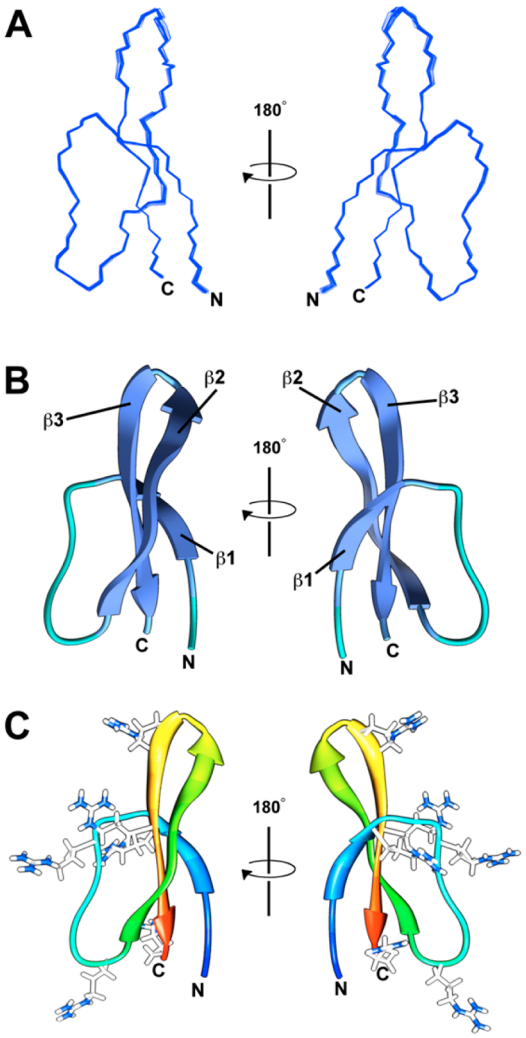

Figure 4. NMR solution structure of 340 μM $^{13}C,^{15}N$-$HD5_{ox}$ in 90:10 H_2O/D_2O at pH 4.0. (A) Overlay of the best 20 structures selected from 400 calculated conformers. RMSD for backbone atoms, 0.135 Å; RMSD for heavy atoms, 1.352 Å. (B) Ribbon diagrams illustrating the β-sheet structure of $HD5_{ox}$. (C) Depiction of the arrangement of the six Arg residues.

from a Carr-Purcell-Meiboom-Gill (CPMG) relaxation dispersion experiment. T_1/T_2 data for the well-structured beta-turn region were used to estimate correlation times. The average T_2 value from this beta-turn region defined by Ile^{22}-Leu^{26} is 181.2 ms, which corresponds to a τ_c of ca. 3.5−3.7 ns. The τ_c was also determined using the ^{15}N-TRACT method, which relies on the transverse relaxation optimized spectroscopy (TROSY) principle.[67] This method gives estimates of τ_c that are independent of exchange phenomenon, which can complicate the interpretation of T_2 measurements. This approach afforded a τ_c value of ca. 4.1 ns, which is in good agreement with the T_2 analysis of the beta-turn loop and estimates a molecular weight of ca. 6.8 kDa. Both methods indicate that $HD5_{ox}$ exists as a dimer under the NMR sample conditions.

Outside of the Ile^{22}-Leu^{26} beta-turn region, the T_2 values are highly variable, whereas the T_1 values are nearly equal (Figure 5A). Many residues exhibit T_2 values that are shorter than the T_2 values for the Ile^{22}-Leu^{26} beta-turn region (e.g., residues 5−7, 10−14, 16−17, 19, 27, 30, 31), indicating that these residues

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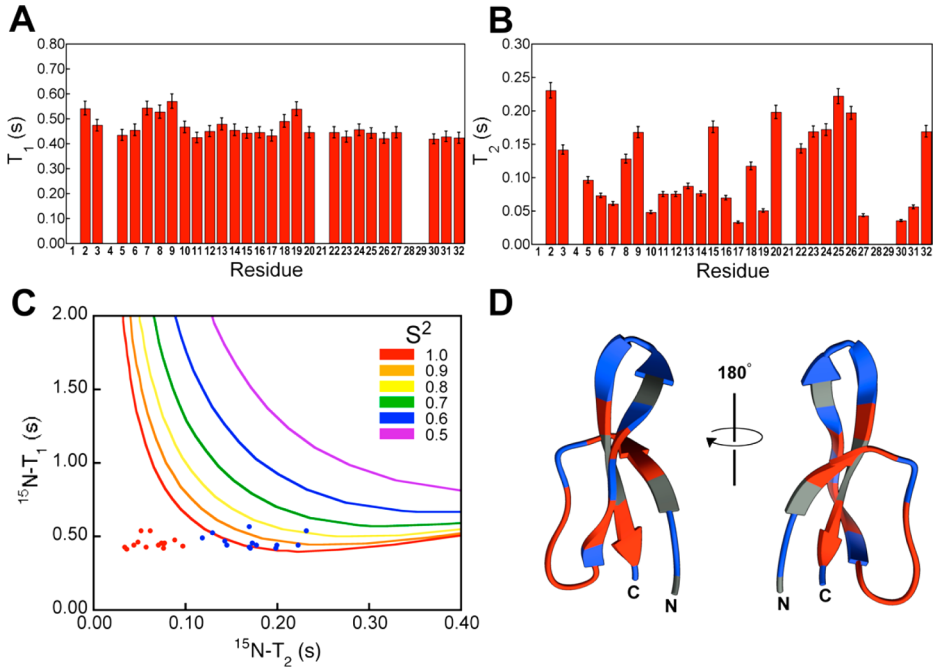

Figure 5. Relaxation studies and dynamics of 340 μM ^{13}C,^{15}N-HD5$_{ox}$ in 90:10 H_2O/D_2O at pH 4.0. (A) T_1 data. (B) T_2 data. (C) Plot of T_1 versus T_2 with theoretical order parameters (S^2 values) for data collected at 600 MHz. Red dots: Residues with T_2 < 0.12 s. Blue dots: Residues with T_2 > 0.12 s. (D) NMR structure of HD5$_{ox}$ where T_2 values <0.12 s or >0.12 s are colored in red or blue, respectively. The gray regions indicate unobserved residues.

may undergo conformational exchange broadening (Figure 5B). To determine whether these residues are indeed exchange broadened, we plotted T_1 values versus T_2 values (Figure 5C). In addition, we overlaid the theoretical values of T_2 and T_1 for a range of correlation times using the standard 'Model Free' formalism of Lipari and Szabo[68,69] and for various order parameters (S^2 values) for data collection at 600 MHz. A S^2 value of 1.0 indicates a rigid structure, whereas lower S^2 values point to flexibility on the microsecond or faster time scale. Figure 5C reveals that many residues fall to the left of the S^2 = 1.0 line, indicating that these residues are most likely exchange broadened on a time scale of milliseconds. This large amount of exchange broadening is consistent with the difficulties encountered in assigning the backbone of HD5$_{ox}$.

NMR Solution Studies of Disulfide Deletion Mutants. 1-D ^{1}H and 2-D ^{1}H,^{15}N-HSQC NMR spectra were recorded for all regioisomers of HD5[Ser^{3,31}]$_{ox}$ and HD5[Ser^{10,30}]$_{ox}$ (Figures S7, S8, and S20–S26). In all cases, the chemical shift dispersion of the amide HN region was less than 1 ppm and comparable to the dispersion observed for unstructured HD5$_{red}$ (Figure 3). Moreover, many of these spectra exhibited greater than 31 amide resonances, which suggested that multiple species exist in aqueous solution at pH 4.0. The disulfide deletion mutant peptides each lack structural organization in aqueous solution. As a result, no further NMR spectroscopic characterization of these peptides was pursued.

Sedimentation Velocity Studies of HD5$_{ox}$ Quaternary Structure. A series of SV experiments was conducted to evaluate the sedimentation behavior of HD5$_{ox}$ under a variety of conditions, and the results from all SV experiments are summarized as Supporting Information (Tables S7–S11 and Figures S27–S30). At pH 7.0 in 10 mM sodium phosphate buffer, conditions similar to those routinely employed for *in vitro* defensin antibacterial activity assays,[12] a single peak at 1.8 S is observed over the range $s_{20,w}$ = 0.7–3.7 S in both the Gaussian fit of the observed $g(s^*)$ peak and in $c(s)$ (Figure 6). The Gaussian fit supports the existence of a single species, and the single peak in $c(s)$ precludes the presence of fast association kinetics between various oligomeric states.[60] To evaluate whether the S-value exhibits concentration dependence, HD5$_{ox}$ samples ranging from 30 to 437 μM were evaluated (Figure S27). In all cases, one sedimentation coefficient of ca. 1.8 S was obtained by the $g(s^*)$, $c(s)$, and dc/dt methods (Table S7), which supports a monodisperse oligomerization state at pH 7.0 over this concentration range and also suggests a dissociation constant below 30 μM for the 1.8 S species.

The HD5$_{ox}$ S-value decreased as the pH was lowered from 7.0 to 2.0 across a range of sample concentrations (10 mM sodium phosphate buffer). Sedimentation coefficients of 1.8 S (pH 7.0), 1.6 S (pH 6.0), 1.2 S (pH 4.0), and 1.0 S (pH 2.0) were obtained by DCDT+ analysis, which provided evenly distributed single-Gaussian fitting of the absorbance raw data as corrected $s_{20,w}$ values (Table S8, Figure S28).

Substitution of phosphate buffer with Tris or HEPES buffer had a negligible effect on the sedimentation of HD5$_{ox}$ at pH 7.0 (Tables S9 and S10 and Figure S29). Average sedimentation coefficients of ca. 1.6 S over a range of peptide concentrations were obtained for HD5$_{ox}$ in Tris or HEPES buffer, respectively. Moreover, millimolar concentrations of Mg(II) and Ca(II) had negligible impact on the HD5$_{ox}$ sedimentation coefficient when added to either Tris or HEPES buffer at pH 7.0 (Tables S9 and S10 and Figure S29). These data demonstrate that physiological concentrations of Mg(II) and Ca(II) do not influence HD5$_{ox}$ quaternary structure in aqueous solution. Moreover, up to 500 mM NaCl had no effect on the sedimentation coefficient of HD5$_{ox}$ at pH 7.0 (10 mM sodium phosphate buffer) (Table S10, Figure S30).

Using both the NMR solution structure and the X-ray crystal structure of HD5$_{ox}$ as models, sedimentation coefficients were

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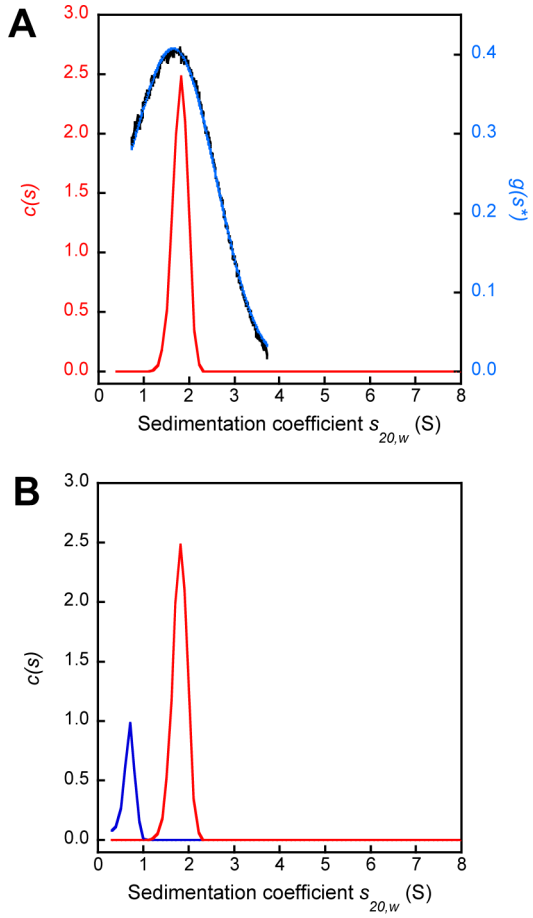

Figure 6. Sedimentation coefficient determination for $HD5_{ox}$ and HD5[Ser^{hexa}] at pH 7.0 (10 mM sodium phosphate buffer) by analytical ultracentrifugation. (A) Sedimentation coefficient determination for 301 μM $HD5_{ox}$. The black curve is the apparent sedimentation coefficient distribution $g(s^*)$. The blue curve is the single Gaussian fit of this data. The red curve is the diffusion-deconvoluted sedimentation coefficient distribution $c(s)$. These analyses provide a *S*-value of 1.8 S and indicate that $HD5_{ox}$ is tetrameric under these experimental conditions. (B) Comparison of the diffusion-deconvoluted sedimentation coefficient distributions of 91 μM HD5[Ser^{hexa}] (blue) and 301 μM $HD5_{ox}$ (red). Additional sedimentation velocity data for $HD5_{ox}$ and mutant peptides are provided as Supporting Information.

estimated using HYDROPRO to be 0.66 S (monomer), 1.16 S (dimer), and 1.71 S (tetramer) (Table S3). The $HD5_{ox}$ homodimer observed in the crystalline form was employed to calculate the dimer sedimentation coefficient. Two different models of $HD5_{ox}$ tetramers were generated from the crystallographic structure and evaluated, and each provided the same predicted *S*-value. A comparison of the experimentally obtained and calculated *S*-values indicates that $HD5_{ox}$ exists in a tetrameric form in aqueous buffer at neutral pH at concentrations ≥30 μM. Moreover, this comparison suggests that pH modulates $HD5_{ox}$ quaternary structure and that dimers predominate at lower pH.

Equation 2 was employed to determine minimum frictional ratios (f/f_0) and thereby provide a semiquantitative analysis of maximum shape asymmetry for $HD5_{ox}$. In all cases, the f/f_0 ratio was ~1.2, which suggests that the HD5 oligomers exhibit globular shape. No extended elongation is predicted for the tetrameric form.

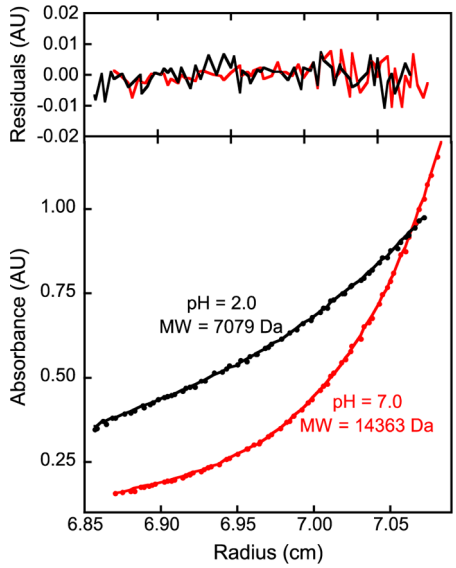

Figure 7. Sedimentation equilibrium of 189 μM $HD5_{ox}$ at pH 2 (black) and 187 μM $HD5_{ox}$ at pH 7 (red) in 10 mM sodium phosphate buffer. Top panel: The residuals of the fits. Bottom panel: Sedimentation equilibrium data (circles) and fits (lines) at a rotor speed of 36 000 rpm. Additional sedimentation equilibrium data for $HD5_{ox}$ and mutant peptides are provided as Supporting Information.

Sedimentation Equilibrium Studies of $HD5_{ox}$ Quaternary Structure. SE experiments were subsequently conducted to determine the molecular weight of the $HD5_{ox}$ species observed to sediment at 1.8 S (Figures 7 and S31–S36). Samples of varying $HD5_{ox}$ concentrations were used to collect absorbance equilibrium profiles at speeds appropriate for a ~14 kDa globular peptide (10 mM sodium phosphate buffer, pH 7.0). After global analysis of six different $HD5_{ox}$ samples at pH 7.0, each at three different rotor speeds, the calculated molecular weight was determined to be 14 363 Da. This value is within 1% error of the theoretical molecular weight of a $HD5_{ox}$ tetramer (14 328 Da). The globally fit value has a standard deviation of ±32 Da and at the 95% confidence interval ranged from 14 472–14 716 Da using a Monte Carlo analysis of fit (Table S12). This analysis was extended to $HD5_{ox}$ samples at varying pH, and the molecular weight calculations of samples prepared at pH values of 4.0, 6.0 and 8.0 also converged to tetrameric molecular weights; however, the global reduced chi-squared values increased with decreasing pH from 7.0 to 4.0. The data obtained at pH 4.0 could be fit using the molecular weight of a $HD5_{ox}$ dimer, but the residuals of the fit were poor compared to those obtained after converging to a tetramer molecular weight (Figures S34 and S35). Moreover, a markedly different sedimentation profile of $HD5_{ox}$ at pH 2.0 was observed and afforded a best-fit molecular weight of 7079 Da (Figure 7). This molecular weight corresponds to a dimer within 2% error (7164 Da). These results confirm that the $HD5_{ox}$ oligomerization state in aqueous solution is pH-dependent with dimers predominating at relatively low pH and tetramers forming at higher pH values.

Sedimentation Velocity Studies of Disulfide Mutant Quaternary Structure. To evaluate the consequence of disulfide bond deletion on quaternary structure, SV experiments were performed with the regioisomers of HD5[$Ser^{3,31}$]$_{ox}$ and HD5[$Ser^{10,30}$]$_{ox}$, in addition to HD5[Ser^{hexa}], at pH 7.0 (10 mM sodium phosphate buffer). Regardless of peptide

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concentration and method of analysis (e.g., $c(s)$ and dc/dt), each peptide exhibited sedimentation coefficient values that were markedly and consistently lower than those of wild-type $HD5_{ox}$ obtained under the same conditions (Table S5 and Figures S37−S39). The sedimentation coefficient values for the $HD5[Ser^{3,31}]_{ox}$ and $HD5[Ser^{10,30}]_{ox}$ regioisomers averaged ca. 0.80 S and ca. 0.90 S, respectively. These values fall between the HYDROPRO-calculated *S*-values for the HD5 dimer (1.16 S) and monomer (0.71 S) The hexa mutant sedimentation coefficient averaged ca. 0.67. These results demonstrate that loss of the Cys^3−Cys^{31} or Cys^{10}−Cys^{30} disulfide bond, or linearization of the peptide backbone, prohibits tetramer formation at pH 7.0. Linearization affords a monomeric, random coil species. Loss of one disulfide bond results in one or more unfolded species that may be described as lower-order oligomers. HYDROPRO calculations of energy-minimized random coil structures of these disulfide deletion mutants also supported the presence of monomeric species.

DISCUSSION

In this work, we present the results of biophysical investigations designed to probe the solution structure and oligomerization properties of the human host-defense peptide $HD5_{ox}$ and a family of disulfide deletion mutants. First, multidimensional NMR spectroscopy afforded the $HD5_{ox}$ solution structure (Figure 4) and confirmed a dimeric oligomerization state under the NMR sample conditions. Second, analytical ultracentrifugation experiments conducted over a range of pH values and in the presence and absence of millimolar Na(I), Ca(II), and Mg(II) delineated factors that contribute to $HD5_{ox}$ oligomerization in aqueous solution. One particularly noteworthy observation is the effects of buffer and pH on the formation and disassembly of $HD5_{ox}$ tetramers (Figure 7). Lastly, complementary studies of disulfide array mutant peptides and $HD5_{red}$ confirmed that the native α-defensin scaffold, defined by the tridisulfide array, is essential for structural rigidity and the formation of well-defined oligomeric species. Taken together, these studies afford insights into the solution behavior, oligomerization properties, and disulfide array of $HD5_{ox}$, which provide a basis for further understanding its biological activities and evaluating its structure and function in the context of other α-defensin family members.

All α-defensins share the same regiospecific pairing of cysteine residues (I−VI, II−IV, III−V, with Cys numbered sequentially from N- to C-terminus) and a three-stranded β-sheet fold. Other conserved features include an invariant Gly residue (Gly^{18} in HD5) and the Arg−Glu salt bridge. Nevertheless, the primary amino acid sequences and overall charges of α-defensins are variable, affording diverse structural dynamics and biological activities, and necessitating evaluation of α-defensin family members on a case-by-case basis.

Atomic-level solution structural characterization is important for elucidating structure/function relationships of antimicrobial peptides.[70] Comparison of the $HD5_{ox}$ solution structure with other α-defensin structures reveals noteworthy similarities and differences. Crystallographic characterization of $HD5_{ox}$ provided several different monomeric forms (PDB: 1ZMP).[10] Overlay of the $HD5_{ox}$ solution structure and the $HD5_{ox}$ crystallographic monomers shows marked topological agreement and provides a RMSD of 1.042 Å for heavy backbone atoms (Figure S40). Likewise, the backbones of $HD5_{ox}$ and HNP3 (PDB: 1DFN) are highly similar with a RMSD of 1.073 Å (Figure S41). The cysteine residues of HNP3 and HD5 share primary amino acid sequence positions, and both peptides exhibit well-defined N- and C-termini in solution (Figure S41). Although $HD5_{ox}$ shares the overall α-defensin fold of rabbit kidney-defensin RK-1[71] and murine cryptdin-4,[43] the latter two peptides exhibit markedly increased conformational flexibility at the N- and C-termini that results from the positioning of the I and VI cysteine residues (Figure S41B). The biological ramifications of variable termini flexibility in α-defensins are currently unclear; however, studies of β-defensins indicated that termini flexibility may contribute to oligomerization.[72]

The disulfide array imposes the α-defensin topology exhibited by HD5 and other family members, and also confers protease resistance. The NMR studies of the disulfide deletion mutants are in agreement with prior NMR characterization of cryptdin-4 disulfide array mutants[42] and reduced HBD-1,[64] and further confirm that disulfide deletion results in a loss of peptide fold. Moreover, the ^1H,^{15}N-HSQC spectra of mutants lacking a single disulfide bond indicate that multiple species are present in solution. Guided by the sedimentation coefficients obtained for the $HD5[Ser^{3,31}]_{ox}$ and $HD5[Ser^{10,30}]_{ox}$, which fall between the calculated *S*-values of the $HD5_{ox}$ monomer and dimer, we contend that the speciation may result from mixtures of oligomeric species.

Recent mutagenesis studies have highlighted the importance of both electrostatics and hydrophobicity in human α-defensin antibacterial action.[4,35−37] Electrostatic and hydrophobicity depictions of select α-defensins are provided as Supporting Information (Figures S42−S47). The primary amino acid sequence of HD5 contains six arginine residues (Figure 1). Arg^6 is involved in the salt-bridge, and the five remaining Arg residues are distributed along one side of the tertiary surface (Figure 4C). The opposite face contains a largely hydrophobic and slightly concave area. This region houses Val^{19}, Ile^{22}, and Leu^{29} in addition to Cys^3−Cys^{31} and Cys^5−Cys^{20}. Only one charged residue, Glu^{21}, is located on this face (Figure S43), and it is adjacent to the tight beta type-I turn. $HD5_{ox}$ therefore exhibits amphipathic character. Many defensins are amphipathic in nature, and this attribute is generally accepted to be important for membrane interactions and antimicrobial activity.[4] Nevertheless, the number and arrangement of Arg residues in α-defensins are variable, and $HD5_{ox}$ exhibits a relatively well-defined cluster of Arg residues on one topological surface as compared to HNPs and cryptdin-4 (Figures S19 and S44). This feature is likely relevant to the $HD5_{ox}$ mechanism(s) of antimicrobial action. Along such lines, replacement of select Arg residues with Ala or Lys attenuated the antibacterial activity of $HD5_{ox}$ against several bacterial species.[28]

The propensity of defensins to self-associate and form oligomers is considered to be important for various biological functions, including bacterial membrane disruption and antiviral activity.[4] Nevertheless, few thorough investigations of defensin quaternary structure are in the literature, and how sample conditions contribute to the observed oligomerization states are largely unknown. Biophysical characterization of the θ-defensin retrocyclin-2 exemplified the importance of buffer composition for oligomerization.[73] The first crystallographic characterization of an α-defensin revealed HNP3 in a dimeric form,[66] and this structural feature was hypothesized to be important for bacterial membrane permeabilization. Later solid-state NMR spectroscopic studies of HNP1 suggested a dimer pore mechanism of membrane disruption.[74] Recent investigations demonstrated the importance of HNP1 dimerization

in antibacterial activity, anthrax lethal factor inhibition, and binding to HIV-1 gp120.[37] A model of HNP1 tetramerization was also proposed in this work. Crystallographic characterization of other human α-defensins, including HD5 and HNP4, also revealed dimeric forms.[10] Dimers of human β-defensin HBD-3[72] and the plant defensin NaD1[75] have been observed in solution. In contrast, monomers of cryptdin-4,[76] RK-1,[71] and human β-defensins[72] HBD-1 and -2 were identified. Self-assembly of HD6 "nanonets," or higher-order oligomers, was recently described and implicated in protection of the intestinal mucosa from bacterial invasion.[77] Taken together, these studies indicate that defensin oligomerization is highly variable and likely dependent on the sample conditions, making direct comparisons difficult and complicating predictions of oligomeric state.

The dimeric oligomerization state of $HD5_{ox}$ in the NMR sample (90:10 H_2O/D_2O, pH 4.0) was first indicated by analysis of T_2 values and later confirmed by a ^{15}N-TRACT experiment. Indeed, self-association of $HD5_{ox}$ was observed by crystallography and surface plasmon resonance (SPR).[10,35,78] A dissociation constant of ca. 2 μM was obtained from SPR experiments conducted at pH 7.4 and in the presence of 150 mM NaCl, attributed to dimer formation; evidence for higher-order oligomers was reported at $HD5_{ox}$ concentrations greater than ca. 8 μM.[78] Recent mutagenesis studies indicated a hydrophobic mode of dimerization.[35] The structural studies presented in this work further confirm the importance of hydrophobicity in $HD5_{ox}$ quaternary structure. The ^{13}C-edited NOESY spectrum revealed a number of exchange-broadened Hα signals, including those corresponding to residues Cys^{20} and Glu^{21} housed on the outermost sheet of the β-bulge. Exchange broadening of Hα signals was also observed for residues Thr^7 and Cys^{10} of the loop. Exchange broadening was judged to occur at these positions because a lack of recordable data corresponding to these atoms was obtained in the ^{13}C-edited NOESY spectrum. Lastly, the backbone ^{15}N T_2 measurements indicate that specific regions of the peptide undergo conformer exchange broadening (Figure 5B). Asymmetric tumbling is an alternative explanation for the differential levels of T_2 relaxation because this phenomenon results in longer T_2 times away from the center of mass. $HD5_{ox}$ is not a spherical molecule; however we contend that a spherical model for tumbling is sufficient, and differential tumbling along unequal axes does not account for the distribution of T_2 times measured (Figure S48). Residues 22−24 comprising the beta turn are the most distant from the center of mass. These residues exhibit some of the most ideal T_2 values (e.g., close to the $S^2 = 1.0$ line, Figure 5C). The order parameter plots exhibited in Figure 5C are based on the Lipari and Szabo 'model free' theory,[68,69] which assumes spherical tumbling, and suggests that a spherical model for $HD5_{ox}$ tumbling is appropriate for the beta turn residues. In contrast, short T_2 values are observed for many residues in loop 7−14. This loop also traces along points that are distant from the center of mass, and these T_2 values are inconsistent with asymmetric tumbling. We therefore conclude that the T_2 times in $HD5_{ox}$ are indicative of a dimeric interface that is exchanging between free and bound forms on the millisecond time scale.

In contrast, the analytical ultracentrifugation studies presented in this work indicate that $HD5_{ox}$ exists as a tetramer at >30 μM in buffered aqueous solution at neutral pH (Figures 6 and 7). Taking the sedimentation equilibrium results into account, we speculate that the significant peak broadening and heterogeneous signal intensities observed in the ^{1}H,^{15}N-HSQC NMR spectra of ^{15}N-$HD5_{ox}$ prepared in buffered solutions resulted from tetramer formation. Further sedimentation velocity experiments indicated that the tetramer was unaffected by varying the sample concentration or buffer composition (phosphate vs Tris vs HEPES), or by addition of millimolar concentrations of the divalent cations Na(I), Ca(II) and Mg(II). We chose to investigate the consequences of cation addition because the antibacterial activity of HD5 is "salt-sensitive." Like many defensins, addition of millimolar concentrations of NaCl to assay buffer results in attenuated antibacterial activity *in vitro*.[22] This phenomenon is typically attributed to a salt-induced disruption of electrostatic interactions between the defensin and negatively charged bacterial cell surface. The results presented in this work demonstrate that up to 500 mM NaCl does not perturb $HD5_{ox}$ quaternary structure over the peptide concentration range tested, suggesting that disrupted oligomerization does not contribute to attenuated antibacterial activity in the presence of salt. In contrast, the absence or presence of buffer and also pH modulate the $HD5_{ox}$ oligomerization state. In phosphate buffer, $HD5_{ox}$ oligomerization is influenced by pH. The pH effect is evidenced by the *S*-values obtained from the SV measurements and in the SE data (Figure 7). The conclusion that $HD5_{ox}$ is best described as a dimer at pH 4.0 in unbuffered solution and as a tetramer in the presence of 10 mM sodium phosphate at pH 5.0 illustrates the importance of solution composition when evaluating defensin oligomerization states. Indeed, prior solution studies of retrocyclin-2 revealed buffer-dependence.[73] A trimer was obsereved at pH 7.4 in either phosphate or Tris buffer whereas, in unbuffered solution, the trimer was only observed at higher peptide concentrations. Further investigations are required to elucidate the molecular basis for this pH-dependent self-association from dimer to tetramer in addition to residues that comprise the tetramer interface of $HD5_{ox}$.

HD5 is released from Paneth cells into the human small intestinal lumen where it contributes to mucosal immunity. Estimates for the extracellular concentration of Paneth cell defensins vary from 50−250 μg/mL (luminal HD5)[21] to ≥25 mg/mL (cryptdin-4 at the point of secretion).[79] The NMR and AUC studies presented in this work are in this concentration range. Moreover, the AUC investigations cover a pH range relevant to the small intestine in physiological and pathological states. This environment is relatively neutral to slightly alkaline environment under healthy conditions largely as a result of bicarbonate production by the pancreas and mucosa, and becomes more acidic during inflammation.[80] Although the compositions of aqueous buffer and the intestinal mucosa/lumen differ substantially, and various small molecules such as fatty acids present in the gut may influence oligomerization, the results from this investigation suggest that HD5 may exist as a tetramer in the healthy gut. Moreover, it is intriguing to speculate that alterations in HD5 oligomerization, and hence function, may occur as a result of pH fluctuations *in vivo*, e.g., during intestinal inflammation as a result of a more acidic environment.

We previously reported that deletion of a single disulfide bond in $HD5_{ox}$ results in loss of antibacterial activity against *S. aureus*.[12] Taking the current peptide stability and biophysical investigations into account, we conclude that this attenuated activity results from disrupted peptide fold and quaternary structure. Identifying particular cellular targets of $HD5_{ox}$ for a

variety of bacterial species and characterizing the $HD5_{ox}$/target interaction(s) are required to further elucidate precisely how $HD5_{ox}$ contributes to innate immunity and human health.

■ ASSOCIATED CONTENT

Supporting Information

Tables S1−S12 and Figures S1−S48. This information is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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■ ABBREVIATIONS USED

AUC, analytical ultracentrifugation; CFU, colony forming unit; HD5, human α-defensin 5; $HD5_{red}$, reduced human α-defensin 5; $HD5_{ox}$, oxidized human α-defensin 5; HNP, human neutrophil peptide (an α-defensin); HSQC, heteronuclear single quantum coherence; IPTG, isopropyl-β-D-thiogalactopyranoside; LB, Luria Broth; NOESY, nuclear Overhauser effect spectroscopy; OD, optical density; SE, sedimentation equilibrium; SV, sedimentation velocity; TFA, trifluoroacetic acid; TOCSY, total correlation spectroscopy; TROSY, transverse relaxation optimized spectroscopy; TSB, trypticase soy broth

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