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Osteogenesis Imperfecta Missense Mutations in Collagen: Structural Consequences of a Glycine to Alanine Replacement at a Highly Charged Site

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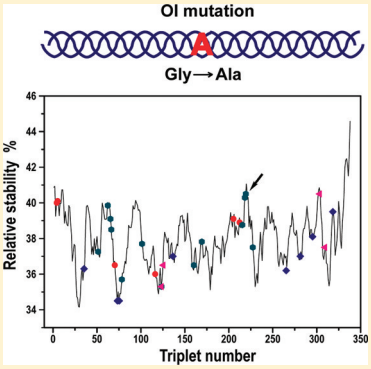
Supporting Information

ABSTRACT: Glycine is required as every third residue in the collagen triple helix, and a missense mutation leading to the replacement of even one Gly in the repeating $(Gly\text{-}Xaa\text{-}Yaa)_n$ sequence with a larger residue leads to a pathological condition. Gly to Ala missense mutations are highly underrepresented in osteogenesis imperfecta (OI) and other collagen diseases, suggesting that the smallest replacement residue, Ala, might cause the least structural perturbation and mildest clinical consequences. The relatively small number of Gly to Ala mutation sites that do lead to OI must have some unusual features, such as greater structural disruption because of local sequence environment or location at a biologically important site. Here, peptides are used to model a severe OI case in which a Gly to Ala mutation is found within a highly stabilizing Lys-Gly-Asp sequence environment. Nuclear magnetic resonance, circular dichroism, and differential scanning calorimetry studies indicate this Gly to Ala replacement leads to a substantial loss of triple-helix stability and nonequivalence of the Ala residues in the three chains such that only one of the three Ala residues is capable of forming a good backbone hydrogen bond. Examination of reported OI Gly to Ala mutations suggests their preferential location at known collagen binding sites, and we propose that structural defects caused by Ala replacements may lead to pathology when they interfere with interactions.



Collagen, the major extracellular matrix structural protein in multicellular animals, is defined by the presence of a triple-helix conformation, formed by supercoiling of three polyproline II-like helical chains. A striking feature of the triple-helix conformation is the strict amino acid sequence pattern it generates, requiring Gly as every third residue.[1−4] Only Gly, which has no side chain, can pack into the center of the triple-helix structure without causing distortion. A missense mutation leading to the replacement of even one Gly in the repeating $(Gly\text{-}Xaa\text{-}Yaa)_n$ sequence with a larger residue leads to a pathological condition. For instance, a Gly missense mutation in the $(Gly\text{-}Xaa\text{-}Yaa)_{338}$ triple-helix domain of the $\alpha1$(I) or $\alpha2$(I) chains of type I collagen, the major collagen in bone, leads to a hereditary bone disorder, osteogenesis imperfecta (OI), characterized by fragile bones.[5] Eight possible amino acids (Ala, Ser, Cys, Asp, Glu, Arg, Val, or Trp), as well as a nonsense codon, can be generated by a single base change in the four available Gly codons, and all of these residues have been observed as Gly replacements in collagen diseases.[6−8] There is evidence that the identity of the residue replacing Gly influences the extent of triple-helix disruption and the OI clinical phenotype.[8−10]

Studies of triple-helical peptide have shown a single Gly substitution in a $(Gly\text{-}Pro\text{-}Hyp)_8$ environment is highly destabilizing, and the identity of the residue replacing Gly was observed to affect the degree of peptide destabilization. The order of stability loss, from least to greatest, was as follows: Ala ≤ Ser < Cys < Arg < Val < Glu ≤ Asp.[11] This ranking has been confirmed by peptides of other design.[12] In all cases, Ala and Ser were seen to have the weakest effect on conformation and stability, and in several cases, Ala was less destabilizing than Ser.[12] The peptide data contrast with results for OI collagens expressed in fibroblasts, where the small degree of destabilization observed (1.5−5 °C) depends on the location of the mutation site but not the residue replacing Gly.[13] The relatively short length of collagen model peptides (~10 tripeptide units) results in substantial destabilization due to local perturbations at a Gly substitution site, in contrast to type I collagen (338 tripeptide units), where global T_m values show only a small decrease.

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Table 1. Peptides Modeling the Gly to Ala Substitution at Residue 658 in the α1(I) Chain at pH 7.0 and 2.9, Showing CD Thermal Transition Temperatures (T_m), Mean Residue Ellipticities at 224 nm (MRE_{224}), and Calorimetric Enthalpies (ΔH_{cal})

peptide name	peptide sequence[a]	pH	T_m (°C)	MRE_{224} (deg cm^2 dmol^{-1})	enthalpy (kJ/mol)
T1-645	Ac-GPO-GAK-GEO-GDA-GAK-**G**DA-GPO-GPO-GPO-GPO-GPO-GY-$CONH_2$	7.0	31.5	3950	280
		2.9	22.5	3800	–[b]
T1-645[G16A]	Ac-GPO-GAK-GEO-GDA-GAK-**A**DA-GPO-GPO-GPO-GPO-GPO-GY-$CONH_2$	7.0	12	2310	140
		2.9	12	1650	150
T1-655	Ac-GPO-GPO-GPO-GPO-GAK-**G**DA-GPO-GPO-GPO-GPO-GPO-GY-$CONH_2$	7.0	55	3800	320
		2.9	50	3750	270
T1-655[G16A]	Ac-GPO-GPO-GPO-GPO-GAK-**A**DA-GPO-GPO-GPO-GPO-GPO-GY-$CONH_2$	7.0	30	3670	285
		2.9	25	3530	202

[a] ^{15}N-labeled residues are underlined, and mutated residues are shown in bold. [b] Two transitions were seen for T1-645 at pH 2.9 by DSC, but not by CD, which may relate to different heating rates.

The identity of the residue replacing Gly also appears to influence the clinical severity of osteogenesis imperfecta. Ser and Cys, the most frequent replacement residues, are found in lethal OI cases less often than expected, while Val, Asp, Glu, and Arg occur more often than expected in lethal cases of OI.[8,14] Most strikingly, Ala is highly underrepresented in reported OI cases, as well as in all other collagen diseases, suggesting that in many cases Gly to Ala changes may result in a mild phenotype that escapes clinical classification.[8,14] In the current OI database,[6,7,15] there are 33 Gly to Ala replacements reported (5.7%) of a total of 581 Gly missense mutations in the α1(I) chain, and only four of these Gly to Ala mutations lead to the most severe OI clinical phenotype, perinatal lethal type II. With the extensive number of OI mutations reported, there are now a significant number of multiple OI cases due to different mutations occurring at a single Gly residue site in the α1(I) or α2(I) collagen chain;[7,8,15] in the large majority of cases, an Ala mutation leads to an OI type less severe than that seen for other replacement residues at the same site (Table S1 of the Supporting Information). For example, a Gly to Ala mutation at position 637 leads to type I OI (mildest form), while a Gly to Val mutation at position 637 leads to type II OI (perinatal lethal).[15]

Previous studies of model peptides indicate that a Gly to Ala replacement results in a major destabilization of the triple helix, even though the degree of destabilization is smaller than that observed for replacements with larger residues.[11,16] The high-resolution X-ray structure of a peptide with a Gly to Ala substitution within a highly stabilizing and rigid $(Pro-Hyp-Gly)_{10}$ context shows a highly localized distortion, with replacement of the three standard direct interchain (Gly)-NH···CO(Pro) hydrogen bonds with water-mediated (Ala)-NH···H_2O···CO(Pro) hydrogen bonds.[1,17] In addition, the angular distortion puts the two helical ends out of register. Nuclear magnetic resonance (NMR) studies of this peptide indicate that the Ala residues at the mutation site are nonequivalent and that the amide of only one of the three Ala residues is capable of forming a good hydrogen bond.[18]

It is not surprising that replacing Gly with the next smallest residue, Ala, might lead to less structural distortion and to milder clinical consequences than replacements with larger residues. The relatively small number of Gly to Ala mutation sites that do lead to OI must have some features that cause them to generate a clinical phenotype. The decrease in thermal stability due to a Gly to Ala substitution has been shown to depend on the local sequence environment in the peptide, with a larger ΔT_m seen in a more rigid, Gly-Pro-Hyp sequence than in a more flexible environment.[12] Thus, one possibility is that observed Gly to Ala replacements that lead to OI are located at sites with unusual amino acid sequence environments that lead to a more disruptive outcome. To investigate this hypothesis, we studied peptides containing the sequence of a Gly to Ala mutation at position 658 in the α1(I) chain, which was observed in a severe case of OI. This mutation is located within a highly charged Lys-Gly-Asp (KGD) local sequence environment. The KGD and KGE sequences were previously shown to contribute an unusually high degree of stability to the triple helix, and computational analysis showed such sequences are present in fibrillar collagens at a frequency much greater than the expected frequency.[19] The effects of the Gly to Ala substitution on the overall conformational stability of the peptide were characterized by circular dichroism (CD) and differential scanning calorimetry (DSC), while the conformation, dihedral angles, and hydrogen bonding were determined at specific sites by NMR. Complete folding around the mutant sequence was achieved when a strong stabilizing $(Gly-Pro-Hyp)_n$ sequence was included at the N-terminus, as well as the C-terminus. The Ala replacement led to a substantial loss of triple-helix stability and significant perturbations to triple-helix structure and hydrogen bonding. Examination of the locations of known Gly to Ala OI mutation sites indicates they are not localized to regions of high or low triple-helix stability, but a significant number are situated within known collagen binding sites. We suggest that the distinct but relatively minor local structural perturbations at Gly to Ala sites lead to observable clinical outcomes when they disrupt biologically important interactions.

MATERIALS AND METHODS

Peptides. Peptides were purchased from Tufts University Core Facility (Boston, MA) or Biomer (Pleasanton, CA) and purified on a Shimadzu high-pressure liquid chromatography C-18 column (Shimadzu, Columbia, MD). The identity was confirmed by matrix-assisted laser desorption ionization time-of-flight (MALDI-TOF) mass spectrometry (Applied Biosystems Voyager DE Pro).

Circular Dichroism Spectroscopy. CD spectra were recorded on an Aviv model 62DS CD spectrophotometer (Aviv Biomedical Inc., Lakewood, NJ). Cells with a path length of 10 mm were used, and the temperature of the cells was controlled using a Hewlett-Packard Peltier thermoelectric temperature controller. Samples were prepared at a concentration of 1 mg/mL in 20 mM PBS (10 mM NaH_2PO_4, 10 mM Na_2HPO_4, and 150 mM NaCl) at pH 7 or in 0.1 M acetic acid

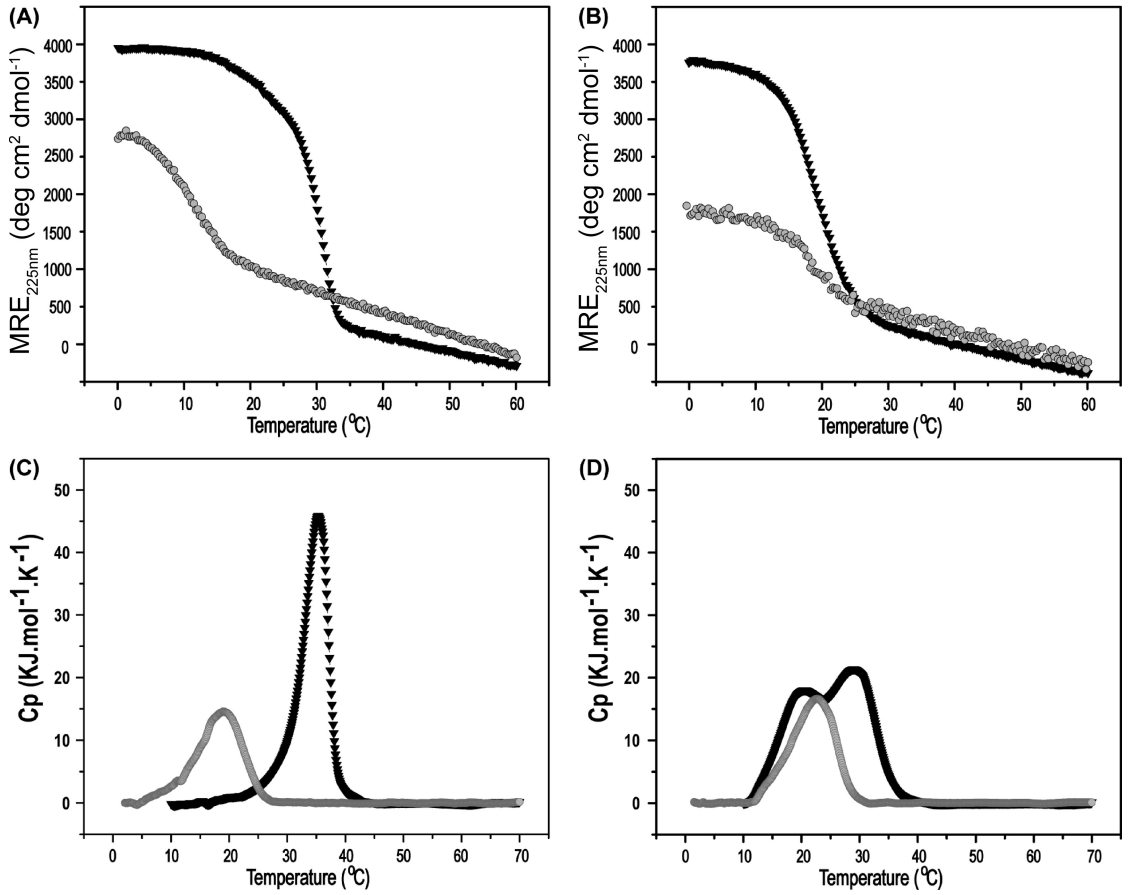

Figure 1. Thermal transitions of peptide set T1-645 with a Gly to Ala mutation. (A) CD thermal transition of T1-645 (black) and T1-645[G16A] (gray) in 20 mM PBS (pH 7.0). (B) CD thermal transition of T1-645 (black) and T1-645[G16A] (gray) in 0.1 M acetic acid (pH 2.9). (C) DSC profile of T1-645 (black) and T1-645[G16A] (gray) in 20 mM PBS (pH 7.0). (D) DSC profile of T1-645 (black) and T1-645[G16A] (gray) in 0.1 M acetic acid (pH 2.9).

at pH 2.9. Peptide concentrations were determined by tyrosine absorbance at 275 nm using an ε^{275} of 1400 M^{-1} cm^{-1}. Wavelength scans were conducted from 190 to 260 nm with a 0.5 nm increment per step and a 5 s averaging time. CD was applied to determine the thermal stability by monitoring the amplitude of the peak at 224 nm as a function of an increasing temperature with an average heating rate of 0.1 °C/min.[20] The melting curve is fit to a trimer to monomer transition, and the melting temperature (T_m) is defined as the temperature at which the fraction folded is equal to 0.5.

Differential Scanning Calorimetry. DSC measurements were performed on a Nano-DSC II, model 6100 scanning calorimeter (Calorimetry Sciences Corp., Lindon, UT). All the peptides were dialyzed in buffers for 24 h before DSC measurements, and their concentrations were determined after dialysis. All DSC profiles were obtained at a scan rate of 1 °C/min, and each curve was subjected to baseline subtraction prior to data analysis.

NMR Spectroscopy. Peptide sets were synthesized with ^{15}N-labeled amino acids at selective positions for NMR characterization (Table 1). Peptide T1-645 was selectively labeled with ^{15}N at position G16, and peptide T1-655 was selectively labeled with ^{15}N at positions G7 and G16. Peptides T1-645[G16A] and T1-655[G16A] were labeled at positions G7 and A16. The samples were prepared in 2 mM PBS buffer (15 mM NaCl) in a 10% D_2O/90% H_2O mixture with concentrations of 2.3−4.5 mM at pH 7 or a concentration adjusted to pH 3 by addition of hydrochloric acid.

NMR experiments were performed on a Varian INOVA 600 MHz spectrometer equipped with a cold probe (Agilent Technologies, Santa Clara, CA) or a Bruker 600 or 700 MHz spectrometer (Bruker BioSpin Corp., Billerica, MA). $^1H-^{15}N$ heteronuclear single-quantum coherence (HSQC) spectra[21] were recorded at 0 °C. The three-dimensional HNHA experiments were performed to measure homonuclear $^3J_{HNH\alpha}$ coupling constants at 15 °C, with a H−H coupling period of 25 ms.[22] The correction factor for the $^3J_{HNH\alpha}$ coupling constants was obtained as described previously.[23] ^{15}N R_1, R_2, and heteronuclear NOE experiments[24−27] were performed at 10 °C. For measurements of amide proton temperature gradients, $^1H-^{15}N$ HSQC spectra were recorded from 0 to 25 °C or from 0 to 30 °C in 5 °C intervals. The samples were equilibrated at each temperature for at least 2 h. Amide proton temperature gradients were obtained by linear regression analysis of the amide proton chemical shifts versus temperature.

All hydrogen exchange experiments were performed at 10 °C and pD 3, because amide proton exchange rates at pH 7 are too fast to be measured. The pD is corrected for the glass electrode solvent isotope artifact.[28] The peptide was equilibrated at 10 °C for 48 h to ensure that the monomer−trimer equilibrium is reached. The sample was then lyophilized, redissolved in 100% D_2O, and quickly transferred to the spectrometer that was equilibrated at 10 °C. A series of HSQC spectra were recorded

as described previously.[29] The hydrogen exchange rates (k_{ex}) were determined by a nonlinear least-squares fit, and protection factor P is calculated as described previously.[24,29,30] All data were processed using NMRPipe[31] and analyzed with Sparky.[32]

RESULTS

Structural Characterization of Peptide T1-645 with a Gly to Ala Mutation. To clarify the effect of Gly to Ala substitutions on triple-helix structure, we designed a peptide to model a Gly to Ala missense mutation at residue 658 in the α1(I) chain, which is reported to lead to a severe OI III case.[15] The immediate surrounding sequence of Gly658 is GAKGDA, and three triplets N-terminal to the mutation site is a KGE sequence (Table 1). Host–guest peptide studies have shown that such KGD and KGE sequences contribute a very large degree of stabilization to the triple helix.[19,33] Initially, as much of the original collagen sequence as possible N-terminal to the mutation site was included in the control peptide, T1-645, with 13 α1(I) residues N-terminal to Gly658, five α1(I) residues C-terminal to it, and a stabilizing C-terminal $(GPO)_4$ sequence [Ac-GPO-GAK-G*EO-GDA-GAK-G*(A*)DA-GPO-GPO-GPO-GPO-GPO-GY-NH_2]. The native collagen sequence is underlined, and the Gly corresponding to residue 658 (G16) was labeled with ^{15}N for site specific NMR studies (Table 1). The homologous peptide T1-645[G16A] containing an Ala at position 16 was also synthesized, where the Ala16 residue at the mutation site and Gly7 N-terminal to the mutation were labeled with ^{15}N, as denoted by asterisks (Table 1).

The control peptide T1-645 in PBS (pH 7) adopts a triple-helix structure as shown by the characteristic CD spectrum with a maximum at 224 nm (MRE_{224} = 3950 deg cm^2 dmol^{-1}) (Table 1). Monitoring the MRE_{224} with an increasing temperature gives a thermal transition with a T_m of 31.5 °C (Figure 1A), a value close to the T_m of 34 °C predicted using the collagen stability calculator.[33] DSC shows a sharp thermal transition with a value 4 °C higher than that seen by CD, because of the faster heating rate[20] (Figure 1C), and indicates a calorimetric enthalpy of 280 kJ/mol. The homologous peptide with the Gly to Ala replacement, T1-645[G16A], had a significantly reduced MRE_{224} (2310 deg cm^2 dmol^{-1}), suggesting that the introduction of Ala led to loss of a substantial amount of triple-helix structure (Figure 1A). CD studies showed the thermal stability was dramatically reduced from 31.5 to ~12 °C (Table 1). DSC confirmed a similar decrease in stability and indicated a 50% decrease in calorimetric enthalpy compared with that of the parent peptide (Figure 1C).

NMR studies were conducted on both the parent and the mutant peptides of T1-645. The HSQC spectrum of peptide T1-645 at pH 7 contains typical features for a triple-helical conformation, with the ^{15}N-labeled residue Gly16 showing three trimer resonances in addition to one monomer resonance, suggesting a monomer–trimer equilibrium in the solution (Figure 2). The triple-helical resonances disappear at 45 °C, a temperature higher than the melting temperatures of the peptides (data not shown). For peptide T1-645[G16A], the HSQC spectrum shows that Gly7 N-terminal to the mutation site has a monomer but no trimer resonances and that Ala16 at the mutation site has only a weak trimer resonance, together with the monomer resonance (Figure 2). These results suggest the peptide adopts a partially folded conformation with a triple-helical C-terminus, a looser or less stable middle region around the mutation site, and an unfolded N-terminal region. Such a

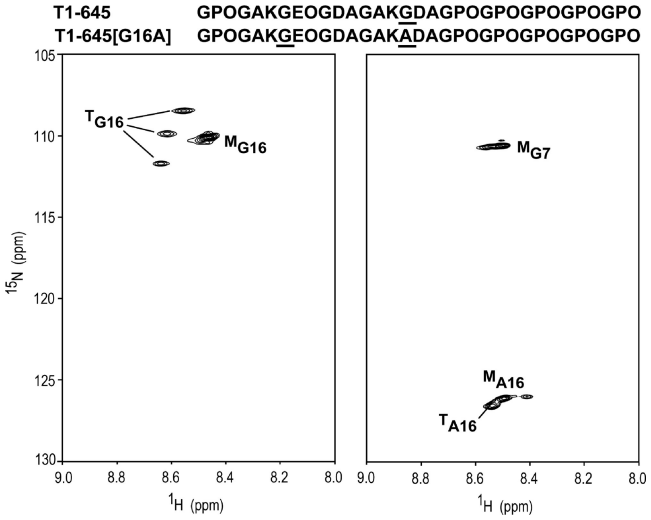

Figure 2. HSQC spectra of peptides T1-645 (left) and T1-645[G16A] (right) at pH 7 PBS buffer at 0 °C. Peptide sequences are shown at the top with ^{15}N-labeled residues underlined. The peaks corresponding to the monomer and trimer states are denoted with superscript M's and T's, respectively.

partially folded molecule is consistent with the observed low ellipiticity, the low stability, and the decreased enthalpies.

In 0.1 M acetic acid (pH 2.9), peptide T1-645 still forms a complete triple helix (MRE_{224} = 3800 deg cm^2 dmol^{-1}) but has a decreased T_m of 22.5 °C, 9 °C lower than that seen for this peptide at pH 7 (Figure 1B). This is consistent with significant electrostatic contributions to stability from the KGD and KGE sequences. At acidic pH, peptide T1-645[G16A] shows a substantial loss of MRE_{224} (1650 deg cm^2 dmol^{-1}) compared with the pH 7 value (2310 deg cm^2 dmol^{-1}), indicating a further decrease in the triple-helical content. The residual triple-helix structure showed a thermal transition near 12 °C (Figure 1B), a value similar to the thermal transition for T1-645[G16A] at neutral pH. The HSQC spectrum of T1-645 at pH 3 shows peaks still indicative of a triple-helix structure, while the spectrum of T1-645[G16A] indicates a partially folded structure (data not shown). The similarity of mutant peptide T_m values at neutral and acidic pH would be expected if the charged KGE and KAD sequences are in unfolded regions, consistent with the NMR results.

Structural Consequences of a Gly to Ala Mutation in Peptide T1-655. The failure of peptide T1-645[G16A] to form a completely triple-helical structure could reflect a folding problem, where the peptide had difficulty incorporating an Ala into a KAD context within a triple helix. To promote folding and stabilization, the parent peptide and its mutant homologue were modified to replace natural α1(I) residues with a $(GPO)_4$ sequence on the N-terminus as well as the C-terminus of the central α1(I) sequence of residues 655–663 (GAKGDAGPO) to form peptide T1-655. In this peptide, ^{15}N-labeled residues were incorporated at positions Gly7 and Gly16. A homologous peptide was made with the Gly to Ala replacement at position 16 to form T1-655[G16A], and ^{15}N-labeled residues were incorporated at positions Gly7 and Ala16 [Ac-GPOGPOG*POGPOGAKA*DAGPO$(GPO)_4$GY-NH_2] (Table 1).

The control T1-655 peptide formed a stable triple helix with an MRE_{224} of 3800 deg cm^2 dmol^{-1} and a high thermal stability of 55 °C (Figure 3A). The excellent agreement of predicted

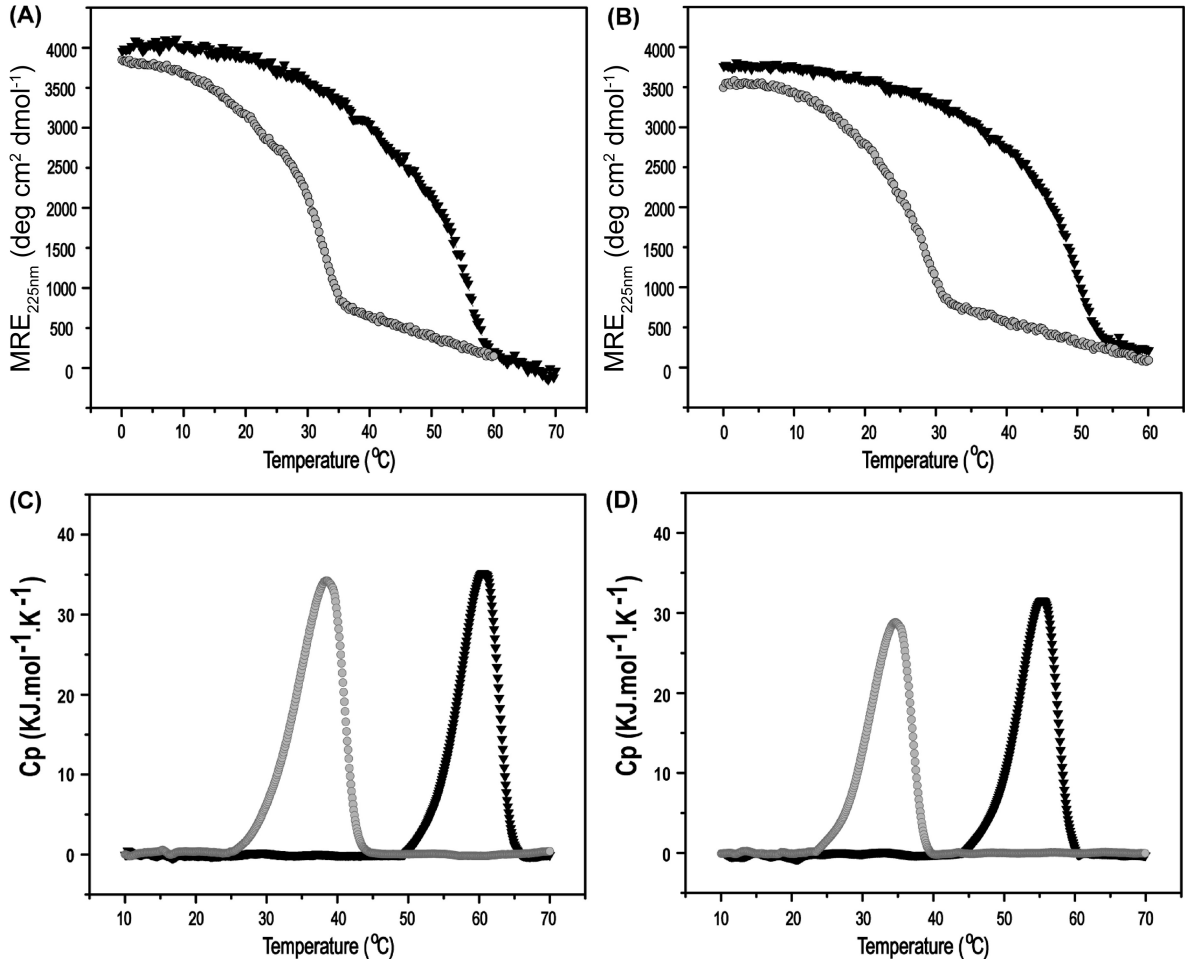

Figure 3. Thermal stability of the Gly to Ala mutant peptide T1-655 set. (A) CD thermal transition of T1-655 (black) and T1-655[G16A] (gray) in PBS (pH 7.0). (B) CD thermal transition of T1-655 (black) and T1-655[G16A] (gray) in 0.1 M acetic acid (pH 2.9). (C) DSC profile of T1-655 (black) and T1-655[G16A] (gray) in PBS (pH 7.0). (D) DSC profile of T1-655 (black) and T1-655[G16A] (gray) in 0.1 M acetic acid (pH 2.9).

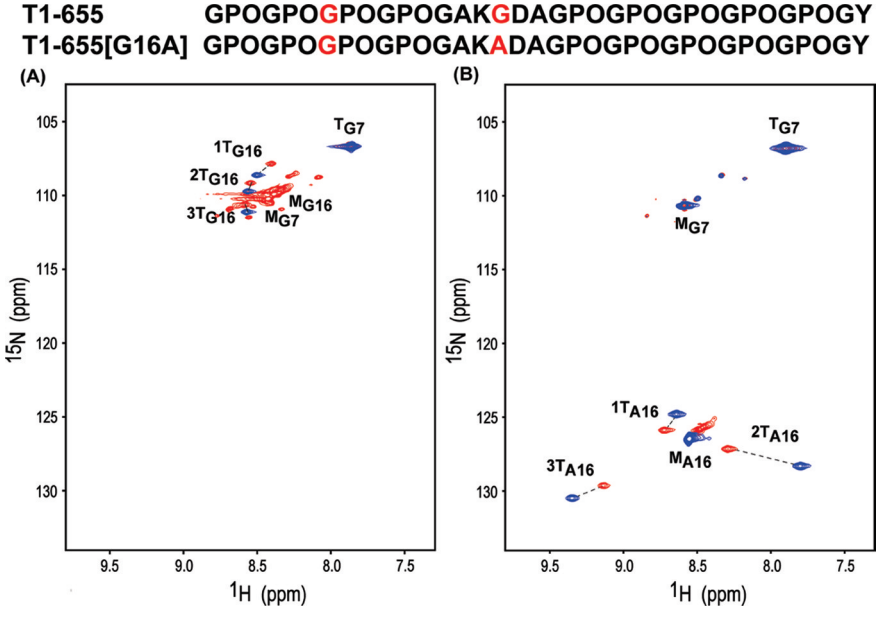

Figure 4. NMR studies of peptide set T1-655. Peptide sequences are shown at the top with ^{15}N-labeled residues colored red. (A) Overlapped ^{1}H−^{15}N HSQC spectra of peptide T1-655 at pH 7 (blue) and pH 3 (red) at 20 °C. (B) Overlapped ^{1}H−^{15}N HSQC spectra of peptide T1-655[G16A] at pH 7 (blue) and pH 3 (red) at 0 °C. The peaks corresponding to the monomer and trimer states are denoted with superscript M's and T's, respectively. Minor monomer resonances arise due to cis−trans isomerization in the unfolded state of the Pro/Hyp-rich chains.[34]

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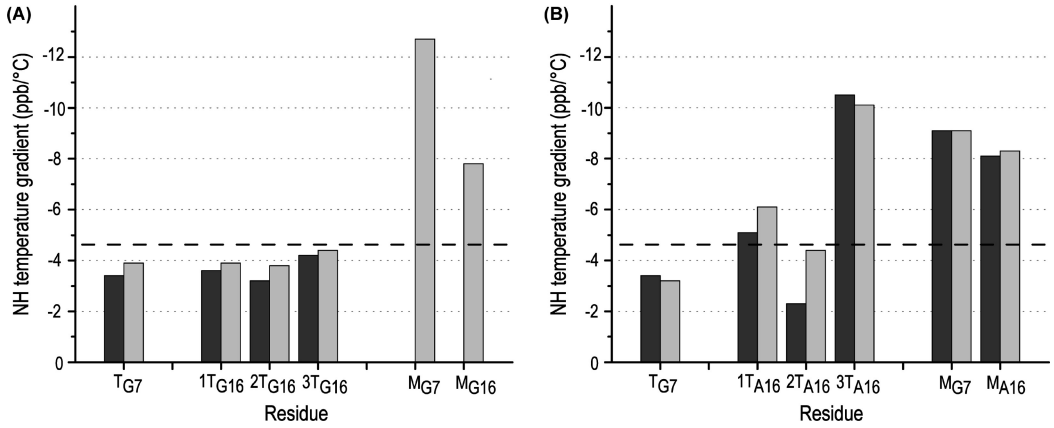

Figure 5. Amide proton NH temperature gradients of peptide set T1-655. (A) Amide proton NH temperature gradient of peptide T1-655 at pH 7 (black) and pH 3 (gray). (B) Amide proton NH temperature gradient of peptide T1-655[G16A] at pH 7 (black) and pH 3 (gray). The black dashed horizontal line corresponds to a value of −4.6 ppb/°C, a cutoff for hydrogen bonding, with less negative values indicative of hydrogen bonding.

(55.2 °C) and observed T_m values again confirms the large (17 °C) stabilizing contribution from KGD in this peptide.[19] The homologous peptide containing the Gly to Ala mutation, T1-655[G16A], now formed a fully triple-helical molecule (MRE_{224} = 3670 deg cm^2 dmol^{-1}), but with a large reduction in stability (T_m = 30 °C) (Figure 3A). There was also a decrease in calorimetric enthalpy (Table 1).

At acidic pH, the T1-655 peptide still appears to be fully helical (MRE_{224} = 3750 deg cm^2 dmol^{-1}), but its T_m is decreased by 5 °C compared with its value at neutral pH, suggesting that the KGD sequence made an electrostatic contribution of approximately this amount to stability (Figure 3B). In 0.1 M acetic acid (pH 2.9), T1-655[G16A] exhibited a small decrease in MRE and a T_m of ∼25 °C. Thus, at acidic pH, the mutant as well as the parent peptide showed a 5 °C decrease in thermal stability compared to that of neutral PBS buffer (Table 1).

NMR Characterization of a Gly to Ala Mutation in Peptide T1-655. NMR studies were conducted on the T1-655 peptide set (Figure 4). The HSQC spectra of peptide T1-655 at pH 7 (PBS) show only one trimer resonance for Gly7, because it is in a repetitive GPO environment, and three trimer resonances for Gly16, where the three different chains have nonequivalent environments due to the one-residue staggering within the triple helix (Figure 4A). The ^{1}H−^{15}N heteronuclear NOE values can distinguish resonances caused by the ordered triple helix (positive values) from resonances due to disordered monomers (negative values) (data not shown). Minor resonances observed in the HSQC spectrum arise due to cis−trans isomerization of Gly−Pro and Pro−Hyp bonds in the peptide in the unfolded states.[10,34] For peptide T1-655[G16A], the HSQC spectrum at pH 7 shows trimer resonances as well as monomer resonances for Gly7 and Ala16. The unique chemical shift of the trimer resonance for Gly7 indicates it adopts a typical $(Gly\text{-}Pro\text{-}Hyp)_n$ triple helix, and the presence of three Ala16 trimer residues indicates some ordered structure at the mutation site (Figure 4B). In contrast to peptide T1-645[G16A], the $(Gly\text{-}Pro\text{-}Hyp)_4$ sequence at the N-terminus of T1-655[G16A] allowed the central region with the mutation to be included within neighboring triple-helix domains.

The NMR spectra were also examined at acidic pH, to assess the effect of removing the Asp charge within the KGD sequence. In peptide T1-655, at pH 3, the trimer resonances for Gly7 and Gly16 are still observed, but they are weaker with respect to the monomer resonances (Figure 4A). Comparison of the HSQC spectra shows that the trimer resonances of Gly7 are completely overlapped at both pH values, indicating no effects of charge on the chemical environment at the N-terminus. However, the three trimer resonances of Gly16 all move upfield in the ^{15}N dimension by ∼1 ppm when the pH changes from neutral to acidic, suggesting an effect of charge on the KGD sequence in the center of the triple helix. Overlaying the HSQC spectra of the T1-655[G16A] peptide at pH 7 and 3 shows that the trimer and monomer resonances of Gly7 are the same at both pH values, while Ala16 shows pH-dependent trimer chemical shifts (Figure 4B). In particular, ^{2T}A16 shifts ∼0.5 ppm in the proton dimension, which could result from changes in conformation and/or dynamics. In addition, the three trimer resonances of A16 are much less dispersed at pH 3 than at pH 7.

The amide proton temperature gradients can indicate the existence of hydrogen bonding for triple-helical peptides. A value greater than −4.6 ppb/°C supports the presence of a hydrogen bond.[18,23] The monomer resonances of Gly7 and Gly16 in T1-655 and T1-655[G16A] at pH 7 exhibit values much more negative than this cutoff value, indicating the absence of hydrogen bonding (Figure 5B). For T1-655, the NH gradient values for Gly7 and Gly16 in the trimer state (approximately −3.6 ppb/°C) support the presence of typical triple-helix hydrogen bonding (Figure 5A). In the mutant peptide, the Gly7 trimer resonance has a value of −3.4 ppb/°C, which is typical for hydrogen-bonded Gly residues in the GPO region.[23] However, the amide gradient values for the three trimer resonances of Ala16 in the mutant peptide are very heterogeneous. One Ala, ^{2T}A16, shows an NH gradient value of −2.3 ppb/°C, a value significantly less negative than −4.6 ppb/°C, which indicates the formation of a typical triple-helix amide hydrogen bond. The NH gradient value for ^{3T}A16 (−10.5 ppb/°C) clearly indicates it is not participating in a hydrogen bond. For ^{1T}A16, the value for the NH gradient (−5.1 ppb/°C) is borderline, consistent with a weaker, transient, or water-mediated hydrogen bond.

At pH 3, the amide gradient studies of peptide T1-655 support hydrogen bond formation for Gly7 and Gly16 trimer resonances and a lack of hydrogen bonding for the monomer resonances, as seen at pH 7 (Figure 5A). The amide gradient values for the mutant peptide again show a Gly7 trimer resonance with a value of −3.2 ppb/°C (pH 3), typical of

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hydrogen bonding residues (Figure 5B). Similar to the pH 7 results, only one Ala, ^{2T}A16, shows an NH gradient value typical of hydrogen bonding, but at pH 3, this ^{2T}A16 shows a more negative value, changing from −2.3 to −4.4 ppb/°C, indicating that the hydrogen bond is weakened. The value for the NH gradient for ^{1T}A16 became more negative at pH 3 (−6.1 ppb/°C), suggesting this borderline hydrogen bond may now be disrupted. These results suggest that lowering the pH from 7 to 3 leads to conformational changes that weaken the remaining hydrogen bonds involving Ala at the mutation site but do not affect the hydrogen bonds of Gly in the N-terminal GPO region.

$^{3}J_{HNH\alpha}$ coupling constants that can be related to dihedral angle φ were obtained for the trimer peaks of peptides T1-655 and T1-655[G16A] from HNHA experiments at pH 7 (Figure S1 of the Supporting Information). Residues in the triple-helical conformation typically contain ϕ angles from −55° to −75° and have a corresponding J coupling value of 4−6 Hz.[29] Labeled residues Gly7 and Gly16 in peptide T1-655 show J coupling values of ∼4 Hz, supporting a standard triple-helix conformation throughout the chain at both pH values. Similarly, Gly7 in peptide T1-655[G16A] shows a J coupling value of ∼4 Hz. In addition, the Ala16 residues in all three chains show J coupling values between 5 and 6 Hz at neutral pH, suggesting that all three Ala residues at the mutation site have dihedral angles similar to that of a typical triple-helix structure when in the current KAD context. Similar results were observed at acid pH, except that for the mutant peptide, the Ala16 trimer resonances in two chains (^{1T}A16 and ^{2T}A16) show small increased values of J coupling going from ∼5.4 to ∼6 Hz, suggesting the possibility of some alteration in the triple-helix structure (Figure S1 of the Supporting Information).

Hydrogen bonding can also be measured using protection factors derived from hydrogen exchange experiments.[24,29] All hydrogen exchange experiments were performed with peptide T1-655[G16A] at pH 3 and 10 °C, because amide proton exchange rates at pH 7 are too fast to be measured. The high protection factor observed for Gly7 at pH 3 indicates that this residue forms hydrogen bonds within the triple helix and is well protected from solvents (Figure S2 of the Supporting Information). The Ala16 residues show much less protection than G7, with varying degrees of protection among the Ala residues in the three chains (Figure S2 of the Supporting Information). ^{2T}A16 shows more protection than the other two, consistent with the amide proton chemical shift coefficients suggesting that ^{2T}A16 is the only Ala capable of forming a reasonable hydrogen bond at pH 3.

^{15}N R_1, R_2, and NOE relaxation experiments were performed for both peptides to determine if the mutation site experiences dynamic changes at the fast, picosecond time scale at different pH values (data not shown). The labeled residues G7 and Gly16/A16 in the trimer states for both peptides have high NOE values of greater than ∼0.6 at pH 7 and 3, indicating that they are rigid on the picosecond time scale.

DISCUSSION

The significant underrepresentation of Gly to Ala mutations in OI suggests that some of these missense mutations in type I collagen chains may not attract clinical attention because of a mild phenotype or late clinical onset.[14] Such an argument is favored by the observation of single Gly to Ala substitutions within otherwise perfect $(Gly\text{-}Xaa\text{-}Yaa)_n$ repeats in several invertebrate fibril-forming collagens.[35−37] If a subset of Gly to Ala missense mutations in the α1(I) or α2(I) chain result in an OI clinical phenotype, there may be definable features that predispose this subset to disruption or pathology. The environment of the mutation could be a predisposing factor, because peptide studies showed the degree of destabilization depends on the local sequence around a mutation.[12] Previously, the presence of a KGE sequence near an OI missense mutation was implicated in structural disruption and clinical severity,[38] suggesting that the proximity of the highly stabilizing KGE and KGD charged sequences may be important. Structural studies with a peptide containing a Gly to Ala substitution at a KGD site are presented here.

A Gly to Ala mutation within a highly stabilizing charged KGD sequence presents an energy barrier to complete triple-helix folding of a peptide containing a natural α1(I) chain N-terminal sequence. This barrier was overcome via placement of a strong folding/nucleation sequence, $(Gly\text{-}Pro\text{-}Hyp)_4$, at the N-terminus and C-terminus of the peptide. In type I collagen, triple-helix folding proceeds from the C-terminus to the N-terminus, and there is a long $(Gly\text{-}Xaa\text{-}Yaa)_n$ sequence N-terminal to the mutation at residue 658 in the triple helix of the α1(I) chain. The presence of a $(Gly\text{-}Pro\text{-}Hyp)_4$ sequence in peptide T1-655 may compensate for the very small number of triplets N-terminal to the mutation in these model peptides. The good agreement between predicted and experimentally observed stability for T1-645 and T1-655 peptides indicates that KGD and KGE sequences are making the same large contribution to stability in these α1(I) sequence environments that they do when they are isolated sequences in a $(Gly\text{-}Pro\text{-}Hyp)_8$ environment in host−guest peptides, which form the basis for stability predictions.[19,33] Because the mutation is located within the charged KGD sequence, features were characterized at acidic and neutral pH values, to clarify electrostatic contributions to stability. The difference in T_m observed for acidic versus neutral pH is much smaller than the total stabilizing contribution of KGD or KGE (∼5 °C vs 15−17 °C), indicating that stabilizing factors in addition to electrostatic interactions are also arising from the Lys and Asp residues. Other stabilizing interactions involving the Lys and Asp side chains could include hydrogen bonding between side chains, backbone carbonyls, or water, which may be less sensitive to pH. When the T_m at pH 7 is compared with the value at pH 3, a ΔT_m of ∼5 °C is seen for the parent peptide (ΔT_m = 55 °C − 50 °C) as well as for the peptide with the mutation (ΔT_m = 30 °C − 25 °C). This suggests that the electrostatic contribution of the KAD sequence is similar to that of the KGD sequence, even though it may have less favorable hydrogen bonding or hydration effects. Low pH was seen to affect structural features in the mutant peptide: the three trimer resonances of A16 are less dispersed, and the one hydrogen bond involving ^{2T}A16 appears to be weakened. Even though all dihedral angles fall within the normal triple-helix range for the mutant peptide, the Ala16 trimer resonances in two chains (^{1T}A16 and ^{2T}A16) show small increased values of J coupling at low pH, going from ∼5.4 to ∼6 Hz, consistent with some changes in conformation or flexibility near the mutation site.

NMR studies of specifically labeled residues within the T1-655[G16A] peptide showed the Gly7 near the N-terminus is in a standard triple helix but that the Ala16 residues at the mutation site are perturbed. The amide displacement, supported by hydrogen exchange studies, indicates that only one of the three Ala residues forms a strong hydrogen bond while a second Ala may form a weaker or water-mediated

hydrogen bond. Despite the perturbations in hydrogen bonding, J coupling values indicate the dihedral angles for the Ala16 residues did not vary significantly from those expected for a standard triple helix. A previous study of a Gly to Ala substitution within a $(Pro\text{-}Hyp\text{-}Gly)_{10}$ peptide showed one of the three Ala residues had a J coupling of 8.6 Hz, which is not compatible with a triple-helix structure,[18] while all three Ala residues seem to be able to participate in a triple-helix structure in the current KAD context. Both Ala and Gly were found to be rigid on the picosecond time scale, suggesting any perturbations are occurring on a much longer time scale. The changes due to the Gly to Ala replacement in the KGD context are similar to those observed previously in the context of other amino acid sequences, including the most rigid Gly-Pro-Hyp context and an uncharged $\alpha1$(I) chain sequence (Table S2 of the Supporting Information).

Analysis of known Gly to Ala mutations shows they are distributed all along the $\alpha1$(I) chain, and the small number of mutations in the $\alpha2$(I) chains do not appear clustered (Figure 6 and Table S1 of the Supporting Information). Examination of the relative stability along the type I triple helix, using the collagen stability calculator,[33] indicates that Gly to Ala missense mutations are found in regions of low, middle, and high stability (Figure 6). Therefore, stability considerations alone cannot predict which Gly to Ala substitutions will lead to a clinical phenotype. Different window sizes were used for the relative stability calculation to determine whether immediate tripeptide residues or longer range factors could be important, but no correlation was found between the severity of OI and the local stability of the Gly to Ala mutations.

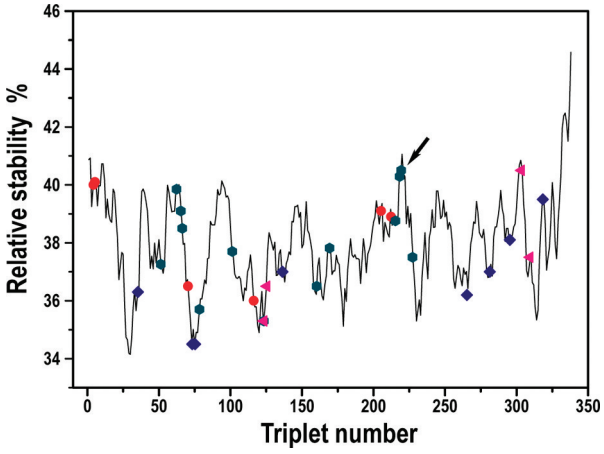

Figure 6. Stability calculation plots with Gly to Ala mutations in COL1A1. The horizontal axis is triplet number from the N-terminus to the C-terminus (from 0 to 338). The Silence classification of OI clinical phenotype is color-coded: red for mild OI I, blue diamonds for mild/moderate OI IV, green hexagons for severe OI III, and pink triangles for lethal OI II. The site of the mutation modeled in peptides is denoted with an arrow.

It has been suggested that Gly missense mutations that disrupt type I collagen binding sites may lead to particularly severe phenotypes or even embryonic lethality,[8,39] and it is plausible that the structural perturbations caused by a Gly to Ala mutation in model peptides could interfere with a collagen interaction site. A number of the Gly to Ala mutations occur in the proximity of known interaction sites (Table S1 of the Supporting Information). Gly220Ala, which is observed in two independently reported cases, is part of a DDR2 binding site as determined by Toolkit peptide analysis.[40,41] The Gly928Ala mutation is near the known Lys/Hyl cross-linking site.[42] The Gly409Ala mutation is C-terminal to a site that binds DDR2, vWF, and SPARC.[40−43] The Gly304Ala mutation is at an $\alpha1\beta1$ integrin binding site.[39,40,44] The number of Gly to Ala missense mutations is also highly underrepresented in type III collagen, where there are only two of 104 cases of Gly missense mutations leading to EDS-IV, at positions 805 and 937.[15] Interestingly, the Gly805 site was in a peptide identified as a binding site for LAIR-1 and LAIR-2,[45] while Gly937 is adjacent to the known cross-linking site KGHR.[42]

The number of recognizable interaction sites located at Gly to Ala mutations suggests that the relatively small distortion caused by Ala replacements may lead to disease when they interfere with binding and biological activity. The site of a Gly to Ala mutation would represent a distorted triple helix with disruption of the screw symmetry of the three chains and significant loss of hydrogen bonding. These features are likely to affect the ability of the triple helix to interact with cell receptors, enzymes, or other matrix components. These mutations would thus represent the result of a natural Ala scanning mutagenesis experiment, in which the clinical phenotype tags those Gly residues necessary for essential interactions.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Figures S1 and S2 and Tables S1 and S2. This material is available free of charge via the Internet at http://pubs.acs.org.

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■ ABBREVIATIONS

OI, osteogenesis imperfecta; T_m, melting temperature; CD, circular dichroism; DSC, differential scanning calorimetry; MRE, mean residue ellipticity. Hydroxyproline is denoted by Hyp in the three-letter code and by O in the one-letter code

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