



Properties of a recombinant human hemoglobin with aspartic acid 99(β), an important intersubunit contact site, substituted by lysine

HIDESHI YANASE,¹ SEAN CAHILL,¹ JOSE JAVIER MARTIN DE LLANO,¹ LOIS R. MANNING,¹ KLAUS SCHNEIDER,¹ BRIAN T. CHAIT,¹ KIM D. VANDEGRIFT,² ROBERT M. WINSLOW,² AND JAMES M. MANNING¹

¹ The Rockefeller University, New York, New York 10021

² University of California School of Medicine, Veterans Affairs Medical Center, San Diego, California 92161

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Abstract

Site-directed mutagenesis of an important subunit contact site, Asp-99(β), by a Lys residue (D99K(β)) was proven by sequencing the entire β -globin gene and the mutant tryptic peptide. Oxygen equilibrium curves of the mutant hemoglobin (Hb) (2–15 mM in heme) indicated that it had an increased oxygen affinity and a lowered but significant amount of cooperativity compared to native HbA. However, in contrast to normal HbA, oxygen binding of the recombinant mutant Hb was only marginally affected by the allosteric regulators 2,3-diphosphoglycerate or inositol hexaphosphate and was not at all responsive to chloride. The efficiency of oxygen binding by HbA in the presence of allosteric regulators was limited by the mutant Hb. At concentrations of 0.2 mM or lower in heme, the mutant D99K(β) Hb was predominantly a dimer as demonstrated by gel filtration, haptoglobin binding, fluorescence quenching, and light scattering. The purified dimeric recombinant Hb mutant exists in 2 forms that are separable on isoelectric focusing by about 0.1 pH unit, in contrast to tetrameric hemoglobin, which shows 1 band. These mutant forms, which were present in a ratio of 60:40, had the same masses for their heme and globin moieties as determined by mass spectrometry. The elution positions of the α - and β -globin subunits on HPLC were identical. Circular dichroism studies showed that one form of the mutant Hb had a negative ellipticity at 410 nm and the other had positive ellipticity at this wavelength. The findings suggest that the 2 D99K(β) recombinant mutant forms have differences in their heme-protein environments.

Keywords: cooperativity; hemoglobin; hemoglobin intersubunit contact; mass spectrometry; mutagenesis

There are several amino acid side chains at the $\alpha_1\beta_2$ subunit contact of hemoglobin A that are very important in the allosteric transition between oxy- and deoxyhemoglobin (Perutz & Ten Eyck, 1971; Perutz, 1990). One of these is Asp-99(β), which is part of an important segment extending from amino acids 94 through 99 at the FG corner of the β -subunit, a region where the largest structural subunit rearrangements occur in the transition between oxy- and deoxyhemoglobin. In this segment the side chains make contacts with some of the opposite side chains of amino acids 36–44 of the C-helix of the α -chain. The major bonding in which Asp-99(β) participates is with Tyr-42(α) (Kinemage 1). Information on the critical nature of Asp-99(β) came

originally from studies with naturally occurring mutant Hb in which the negatively charged side chain was substituted by a variety of other amino acids. These mutant Hb include Hb Kempsey (Asp \rightarrow Asn) (Reed et al., 1968; Bunn et al., 1974), Hb Yakima (Asp \rightarrow His) (Jones et al., 1967), Hb Radcliffe (Asp \rightarrow Ala) (Weatherall et al., 1977), Hb Ypsilanti (Asp \rightarrow Tyr) (Rucknagel et al., 1967), Hb Hotel-Dieu (Asp \rightarrow Gly) (Blouquit et al., 1981), Hb Chemilly (Asp \rightarrow Val) (Rochette et al., 1984), Hb Coimbra (Tamagnini et al., 1991), and Hb Ingelheim (Wajcman et al., 1991) (the latter two have Asp \rightarrow Glu substitutions). All of these natural mutant Hb exhibit an increased oxygen affinity and a decreased cooperativity. Because none of these has a strongly basic amino acid side chain, we decided to substitute a Lys at this site because such a substitution could have profound effects on subunit interactions at the $\alpha_1\beta_2$ interface.

In order to achieve this objective, we used a yeast expression system in which the genes of the α - and β -chains of human globin are expressed on the same plasmid (Wagenbach et al., 1991; Martin de Llano et al., 1993a, 1993b). This expression system

Reprint requests to: J.M. Manning, The Rockefeller University, 1230 York Avenue, New York, New York 10021; e-mail: manning@rockvax.rockefeller.edu.

Abbreviations: Hb, hemoglobin; 2,3-DPG, 2,3-diphosphoglycerate; IHP, inositol hexaphosphate; TFA, trifluoroacetic acid; r, recombinant; PTH, phenylthiohydantoin; TPCK, *N*-tosyl-L-phenylalanine chloromethyl ketone.

does not involve manipulations with fusion proteins; it utilizes the endogenous heme of yeast and produces a soluble Hb that is properly folded and processed at its N-terminal amino acids in the same manner as human HbA. This conclusion is based on comparison of the properties of the recombinant Hb with natural human Hb. In the case of sickle Hb, the criteria were mass spectrometry, amino acid analysis, peptide mapping, HPLC, N-terminal protein analysis, C-terminal protein analysis, reactivity of the Cys-93 SH group, spectral properties, oxygen affinity, cooperativity, response to allosteric regulators, and aggregation of the protein (Martin de Llano et al., 1993a, 1993b). Hence, this system was considered ideal to introduce the desired positively charged substitution at the $\beta 99$ site. This communication describes some unusual properties of this recombinant mutant, i.e., its virtual lack of response to allosteric regulators and its existence in 2 forms.

Results

Purification of the D99K(β) Hb mutant

Yeast harboring the normal human α -globin gene and the β -globin gene mutated to translate for Lys instead of Asp at position 99 did not affect the growth of the yeast. After breakage of the cells and initial batchwise purification on CM-52, the final purification of the D99K(β) recombinant mutant was achieved on HPLC (Fig. 1). The gradient described in the Materials and methods for the purification of the mutant Hb was chosen to ensure the complete removal of several minor components. The major Hb component, which eluted as a symmetrical peak with the main fractions from 34.5 min to 37.5 min, was used for all the structural and functional studies described below.

Characterization of the D99K(β) recombinant mutant Hb

The purified mutant recombinant Hb was subjected to SDS-PAGE, which showed 2 very close and equally intense bands with molecular weights of about 16,000 corresponding to the α - and β -globin chains of Hb (Fig. 2). Analysis of the purified mu-

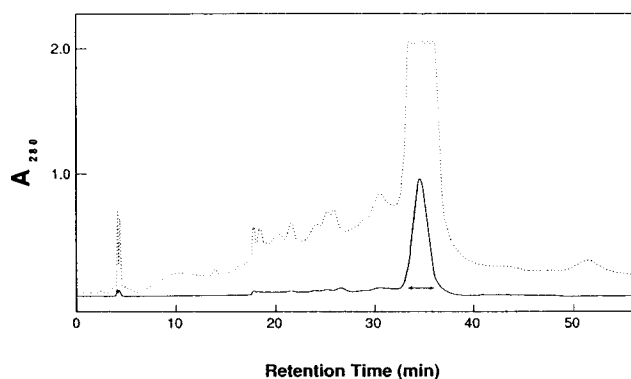


Fig. 1. Purification of D99K(β) mutant Hb by HPLC. The Hb (18 mg) obtained from the yeast extract prepared by chromatography on CM-52 was applied to a SynChropak CM300 column as described in the text. The solid line indicates the absorbance at 280 nm, and the dotted line shows 10 times that absorbance.

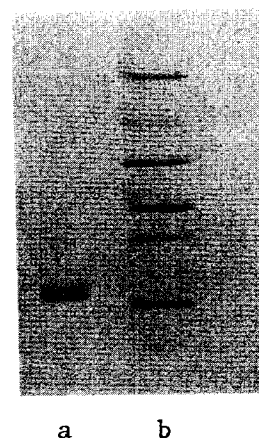


Fig. 2. SDS-PAGE of purified D99K(β) mutant Hb. Lane a, 3 μ g of purified mutant Hb was put onto the gel; lane b, marker proteins were bovine serum albumin (66 kDa), egg white albumin (45 kDa), pepsin (34 kDa), trypsinogen (24 kDa), β -lactalbumin (18.4 kDa), and lysozyme (14.3 kDa). An 18% crosslinked gel was used.

tant Hb in a nondenaturing electrophoresis system (Beckman Paragon) showed a single band, which moved more toward the cathode than did HbA (data not shown), consistent with the substitution of a negative charge by a positive charge in the mutant Hb β -chain.

HPLC separation as described in the Materials and methods gave 1 α - and 1 β -globin chain. The latter eluted earlier than the normal β -chain; the α -chains from the mutant and normal Hb eluted in practically the same position, consistent with the absence of a substitution in the α -chains. Amino acid analysis of the isolated chains was used for their identification (Table 1). For those amino acids for which there are significant differences between the α - and β -chains, i.e., serine, glutamic acid, glycine, alanine, and valine, there was good agreement between the theoretical values and those actually found; the absence of isoleucine was consistent with the known amino acid sequence of human HbA and the mutant recombinant Hb.

Peptide mapping and sequencing

In order to confirm the substitution site, about 300 μ g of each normal and mutant β -chain were digested with TPCK-trypsin and the digests were subjected to HPLC analysis. The pattern of the tryptic peptide map of mutant β -globin chain was compared to the corresponding tryptic map of the normal β -globin chain (Fig. 3). A major peptide from the mutant chain at 40 min retention (bottom panel, open arrow) replaced 1 tryptic peptide from normal HbA (top panel, closed arrow); the rest of both peptide maps had the same profile, consistent with a single substitution on the protein.

The peptide from the mutant Hb (bottom panel) was subjected to sequencing by Edman degradation. The results, shown in Figure 4, indicated a sequence corresponding to that of amino acids 83–102; the underlined Lys was the site of the substitution. The high yield of the PTH-Lys residue at position 99 confirmed that the mutant β -globin chain contained the single amino acid substitution $\beta 99\text{Asp} \rightarrow \text{Lys}$. In this isolated tryptic peptide, there were 2 Lys residues that were not cleaved by trypsin: the Lys⁹⁵–

Table 1. Amino acid analysis of α - and β -chains of recombinant D99K(β)^a

Amino acid	Found		Theory	
	α -Chain	β -Chain	α -Chain	β -Chain
Lysine	10.4	11.3	11	12
Histidine	10.5	9.5	10	9
Arginine	2.8	2.9	3	3
Aspartic acid	11.3	11.0	12	12
Threonine	7.5	6.0	9	7
Serine	<u>11.1</u>	<u>5.3</u>	<u>11</u>	<u>5</u>
Glutamic acid	<u>5.9</u>	<u>11.5</u>	<u>5</u>	<u>11</u>
Proline	6.7	6.9	7	7
Glycine	<u>7.9</u>	<u>12.6</u>	<u>7</u>	<u>13</u>
Alanine	<u>19.0</u>	<u>15.8</u>	<u>21</u>	<u>15</u>
Valine	<u>12.1</u>	<u>15.3</u>	<u>13</u>	<u>18</u>
Isoleucine	0	0	0	0
Leucine	18.0	18.0	18	18
Tyrosine	1.9	1.3	3	3
Phenylalanine	7.6	6.7	7	8

^a For the amino acids in bold, there are significant differences between the amounts in the α - and β -chains and these amounts are underlined. The results were compiled from 2 separate analyses. The values for Thr, Ser, Cys, Met, Tyr, and Trp are low or absent because they are partially or completely destroyed during acid hydrolysis. The values for Val are low because of incomplete hydrolysis of Val-Val bonds during the 24-h acid hydrolysis.

Leu⁹⁶ bond, which is preceded by Asp⁹⁴, and the Lys⁹⁹-Pro¹⁰⁰ bond.

Oxygen binding properties of the D99K(β) mutant Hb

In view of the importance of the Asp-99(β) site in the transition between the oxy and the deoxy states of Hb (Turner et al., 1992), the oxygen binding properties of this mutant were measured (Fig. 5). As reported for the isolated natural Hb that have mutations at this position, the oxygen affinity of the recombinant mutant was increased. However, unlike most of the naturally occurring mutants at this position, the shape of the curve of the D99K(β) mutant Hb indicated that it retained significant cooperativity (Fig. 5, inset; Table 2). Unlike normal HbA, the D99K(β) mutant did not respond to added chloride by undergoing a decrease in its oxygen affinity. Furthermore, it responded only marginally to 2,3-DPG and to added IHP (Table 2).

With the Hem-O-Scan instrument it was not possible to measure the oxygen binding curve of Hb at concentrations lower than about 1.5 mM in heme, but higher concentrations were analyzed to determine any changes in oxygen affinity and cooperativity. Thus, increasing the concentration nearly 8-fold had only a slight effect on the P₅₀ (Table 2). The maximum P₅₀ value attained with the D99K(β) recombinant mutant was about 11 mm Hg, and this oxygen affinity was not further lowered by addition of chloride.

It is important to note that other recombinant Hb expressed in this system, i.e., HbS, have functional proteins that are fully responsive to chloride (Martin de Llano et al., 1993a) and to 2,3-

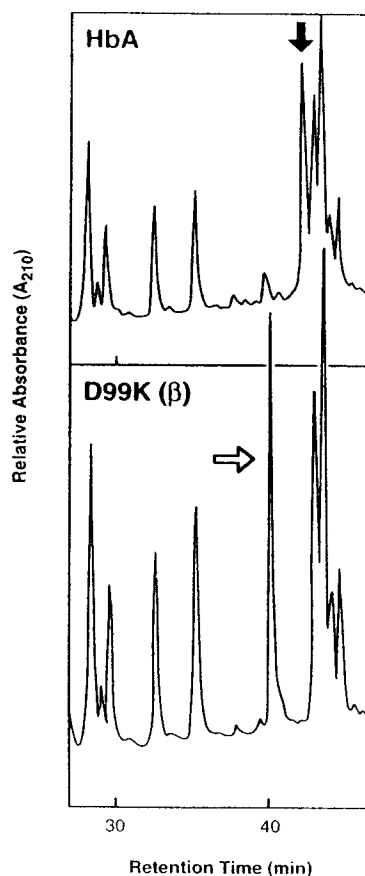


Fig. 3. Tryptic peptide maps of β -chain of D99K(β) mutant Hb and HbA. The only part of the tryptic peptide map shown is the region where the change occurred; the other parts of the maps were identical. The β -chains of each Hb were isolated by HPLC, reduced, carboxymethylated, and digested with TPCK-trypsin, as described in the text. Chromatography was performed on a Vydac C-18 column as described in the text. The closed and the open arrows indicate unique peaks in digests of HbA and D99K(β) mutant, respectively. The peptide in the lower peak (open arrow) from the mutant Hb was subjected to sequencing as described in the text and in Figure 4.

DPG (Table 2). Hence, the lack of a response to chloride is a property of the D99K(β) mutant.

The effect of 2,3-DPG on the oxygen binding of an equimolar mixture of the recombinant mutant Hb and natural HbA was an average of the contribution from each Hb (Table 2). However, this extent of oxygen release was much less than that for HbA in the presence of allosteric regulators. If present in an erythrocyte in such amounts, this mutant Hb would seriously impede the ability of the red cell to release oxygen.

Dissociation of the mutant Hb

The properties of several natural Hb with mutations at Asp-99(β) have been reported in some detail by several investigators (Jones et al., 1967; Rucknagel et al., 1967; Reed et al., 1968; Bunn et al., 1974; Weatherall et al., 1977; Blouquit et al., 1981; Turner et al., 1981, 1992; Rochette et al., 1984; Tamagnini et al., 1991; Wajcman et al., 1991; Doyle et al., 1992). In general, each

Gly⁸³ Thr⁸⁴ Phe⁸⁵ Ala⁸⁶ Thr⁸⁷ Leu⁸⁸ Ser⁸⁹ Glu⁹⁰ Leu⁹¹ His⁹² Cys(Cm)⁹³ Asp⁹⁴ Lys⁹⁵ Leu⁹⁶ His⁹⁷ Val⁹⁸ Lys⁹⁹ Pro¹⁰⁰ Glu¹⁰¹ Asn¹⁰²
 333 134 303 249 111 203 46 162 155 166 - 183 124 122 134 133 108 112 95 87

Fig. 4. Sequence of mutant tryptic peptide from D99K(β). The peptide that was sequenced was isolated as described in Figure 3; the mutant peptide is designated by the open arrow. The values in parentheses are the number of picomoles of each PTH-amino acid found at each cycle of sequencing.

natural mutant showed greater susceptibility toward tetramer-dimer dissociation in both the oxygenated and the deoxygenated states. For example, whereas the dimer-tetramer dissociation constant for normal human HbA is about 10^{-5} M in its oxygenated state and 10^{-10} M in its deoxygenated form (Turner et al., 1981), the corresponding values for the natural mutants at Asp-99(β) are increased by 3–5 orders of magnitude (Turner et al., 1981, 1992; Doyle et al., 1992). We have measured the extent of dimer formation of the oxygenated D99K mutant Hb by several procedures including gel filtration, haptoglobin binding of $\alpha\beta$ dimers determined by filtration of the haptoglobin-Hb dimer complex and by quenching of fluorescence, and by light scattering, as described below.

When the oxygenated D99K(β) mutant Hb (0.4 mM in heme initially) was applied to Sephadex G-75, it eluted in the position corresponding to that of the dimer. Under the same conditions, oxygenated human HbA eluted in a position corresponding to a tetramer.

Light scattering experiments of the oxygenated recombinant D99K(β) mutant Hb showed that, at the Hb concentrations analyzed (0.2 mM in heme), the mutant Hb existed predominantly in the dimeric form (38,000 molecular weight; average of 13 determinations).

Haptoglobin binds Hb dimers instantaneously and very tightly, but tetramers are not bound (Nagel & Gibson, 1967; Benesch et al., 1976). Human HbA undergoes dissociation to dimers more readily in its oxygenated compared to its deoxygenated form (Nagel & Gibson, 1967; Benesch et al., 1976; Doyle

et al., 1992; Turner et al., 1992). Like oxy HbA, the D99K(β) mutant Hb in its oxygenated state dissociated readily to form dimers that combined with haptoglobin (Table 3). Deoxy HbA slowly forms dimers that react with haptoglobin (Doyle et al., 1992; Turner et al., 1992). The value of about 20% dimer formation from deoxy HbA during the time period of the experiment in Table 3 was consistent with its slow dissociation. In the deoxygenated state and at the concentration studied, the mutant D99K(β) Hb bound to haptoglobin much more readily than does deoxy HbA (Table 3), indicating that it was mainly dimeric at this concentration.

The quenching of haptoglobin fluorescence by Hb dimers (Nagel & Gibson, 1967) can also be used to determine the presence of dimers because Hb tetramers do not have this property. As shown in Table 3, the quenching of haptoglobin fluorescence by oxy HbA was readily demonstrated. However, at this concentration (4 μ M in heme), deoxy HbA was present mainly in the tetrameric state and thus shows very little quenching of fluorescence. In contrast, the extent of quenching of fluorescence of both the oxy and the deoxy D99K(β) mutant Hb was about the same as that of oxy HbA. These results are consistent with those found by the other procedures described above and

Table 2. Effect of anions on the oxygen binding properties of recombinant D99K(β) mutant Hb^a

Hemoglobin	Conc (mM)	Addition	P ₅₀	n
HbA (natural)	1.6	0	11	2.5
		0.5 M NaCl	24	2.5
HbS (recombinant)	1.2	1 mM 2,3-DPG	25	3.0
D99K(β)	1.6	0	6	2.1
		0.1 M NaCl	7	2.2
		0.5 M NaCl	6	2.1
		1 mM 2,3-DPG	8	2.3
		1 mM IHP	9	2.2
D99K(β)	0.8	0	10	2.5
+ HbA	0.8	1 mM 2,3-DPG	15	2.7
D99K(β)	3.7	0	8	2.4
D99K(β)	7.3	0	10	ND ^b
		0.1 M NaCl	9	2.5
D99K(β)	14.6	0	11	2.5

^a The P₅₀ values, which are averages of 5 determinations, are expressed in mm Hg and have a precision of ± 1 mm Hg. The Hb concentrations are given as heme values.

^b ND, not determined.

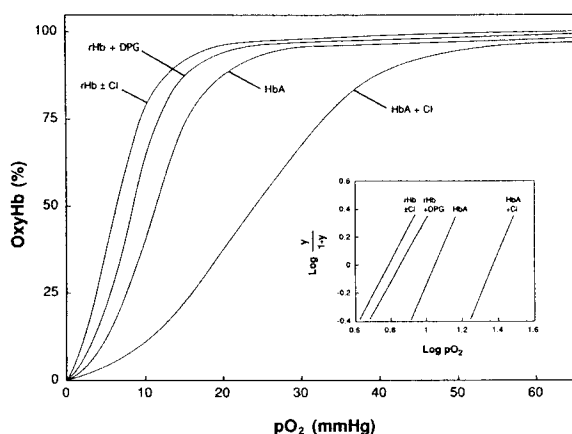


Fig. 5. Oxygen binding curves and Hill plots of D99K(β) recombinant mutant Hb and natural HbA. The oxygen equilibrium curves were determined at 37 °C on Hb (2.0 mM in heme) in 50 mM bis-Tris acetate, pH 7.5. The effect of anions on the oxygen-binding affinity of Hb was determined in the presence of 0.5 M NaCl (Cl) or 1 mM 2,3-DPG as described in the text. Hill plots, the logarithm of the fractional oxygen saturation (y) plotted against the logarithm of the partial pressure of oxygen (pO_2), for each sample are shown in the inset.

Table 3. Haptoglobin binding to normal HbA and recombinant Hb mutant D99K(β)

Hb sample	% Dimer by filtration ^a	% Fluorescence quenching ^b
Oxy HbA	69	55
Deoxy HbA	19	9
Oxy D99K(β)	72	52
Deoxy D99K(β)	71	53

^a In the filtration assay, the concentrations of HbA and the D99K(β) mutant were 2×10^{-6} M in heme. A Centricon 100 was used to determine the amount of dimer bound to haptoglobin, as described in the text. The amount of Hb-haptoglobin complex retained by the filter divided by the total amount of Hb is expressed as the % dimer.

^b In the fluorescence assay, the concentrations of Hb and haptoglobin were 1×10^{-6} M each and the extent of quenching was determined as described in the text.

showed that the mutant was nearly completely dimeric at the concentrations studied.

The data above are to be taken only as an indication of the ease of dimer formation for the mutant Hb and are not meant to indicate that it is dimeric at all concentrations. The measurements, which were performed at Hb concentrations of 0.2 mM in heme or lower, indicated that the mutant Hb in either the oxy or the deoxy state was dimeric at these concentrations. Indeed, we could not detect any tetrameric mutant Hb by any of the 4 methods described above. However, these procedures could not be used at high Hb concentrations. Further studies using modified or novel procedures will be needed to measure any tetramer-dimer dissociation constant of this recombinant Hb with its strongly altered intersubunit contact.

Isoelectric focusing

Analysis of the recombinant D99K(β) mutant by isoelectric focusing showed the presence of 2 somewhat diffuse bands with pI values that differ by 0.1 pH unit (Fig. 6A, lane b). Also shown are the electrophoretic behavior of purified natural HbA from normal red cells (lane c) and recombinant sickle Hb (lane a) from the yeast expression system. The bands from these latter 2 tetrameric Hb were not diffuse like the 2 bands from the D99K(β) Hb. Thus, the doublet pattern of the D99K(β) mutant is not typical of Hb expressed in the yeast system. These bands are referred to as forms D99K(β)-1 and D99K(β)-2.

The 2 forms of the D99K(β) mutant Hb were shown not to be due to oxidation because the spectra of the isolated D99K(β)-1 and D99K(β)-2 (see below) indicated that the amount of met-Hb present, if any, was less than 5%. Second, deliberate oxidation of the D99K(β) mutant with potassium ferricyanide prior to isoelectric focusing resulted in slightly different mobilities of the 2 bands but did not change their relative amounts.

Distribution of the two forms of the D99K recombinant mutant

After isoelectric focusing of different amounts of Hb, the relative intensities of the 2 stained bands were determined by scan-

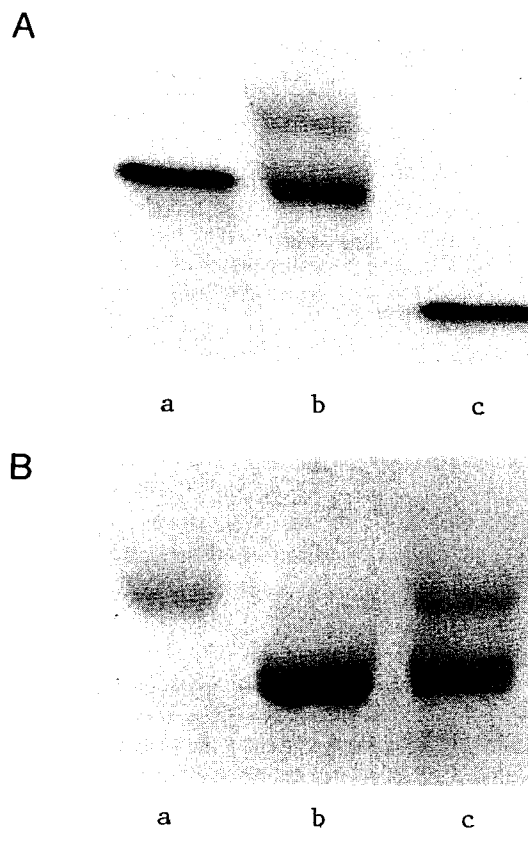


Fig. 6. Isoelectric focusing of D99K(β) mutant Hb. A gel (pH 6–8) (Isolab) was electrophoresed at 10 W for 40 min and stained with 0.2% bromophenol blue. **A:** Lane a, recombinant HbS; lane b, recombinant D99K; lane c, natural HbA. **B:** The separated D99K(β)-1 and D99K(β)-2 bands were eluted from the isoelectric focusing gel as described in the text and then reappplied to a new gel and subjected to isoelectric focusing. Lane a, D99K(β)-1 (60 μ g); lane b, D99K(β)-2 (100 μ g); lane c, fresh D99K(β) (141 μ g).

ning the stained bands on the gel, as described in the Materials and methods. The relative amounts of each were about 40% for the D99K(β)-1 band and about 60% for the D99K(β)-2 band (Table 4).

Separation and properties of the 2 forms of the D99K mutant Hb

After isoelectric focusing, the unstained D99K(β)-1 and D99K(β)-2 forms, which were located by their red color, were eluted from the gel with CO-saturated 50 mM bis-Tris acetate, pH 7.5. They were recovered with a yield of 75% in the approximate ratio of 40:60. A second isoelectric focusing of each separated Hb showed that there was no interconversion of the 2 Hb forms during the electrophoresis (Fig. 6B). Furthermore, the D99K(β)-1 and D99K(β)-2 forms were not formed as a result of the electrophoresis.

The spectral properties of the CO derivatives of the D99K(β) mutant Hb before isoelectric focusing and of the 2 forms separated during isoelectric focusing are given in Table 5. The cor-

Table 4. Distribution of two D99K(β) forms^a

Hb concentration applied (μ M)	D99K(β)-2 (%)	D99K(β)-1 (%)
100	62	39
500	62	39
1,000	65	36

^a The actual Hb concentration during the electrophoresis may be different from the amount applied. After isoelectric focusing, each band was eluted from the gel and the amount of each was determined by densitometry as described in the text.

responding values for HbA are also given for comparison. The results show that the spectral properties of all samples are practically the same at each of the major wavelengths and indicate the absence of met-Hb.

Isolation of the globin chains from major and minor forms

The characterization and sequencing of the mutant tryptic peptide described above were fully consistent with the desired mutation. However, in order to exclude the possibility of an alteration in some other part of the protein chain that could be responsible for the 2 forms of the D99K(β) mutant Hb, the α - and β -globin chains from D99K(β)-1 and D99K(β)-2 were analyzed. HPLC analysis of the unfractionated D99K(β) Hb before isoelectric focusing showed that its β -chain eluted at 18.2 min and the α -chain eluted at 27.4 min (Fig. 7, top panel); the reproducibility was ± 1 min on the HPLC. HPLC analysis of the separated D99K(β)-1 and D99K(β)-2 showed that their β -chains eluted at 18.8 and 18.2 min, respectively, and the α -chains at 28.6 and 27.6 min, respectively (Fig. 7, second and third panels). These values are identical within experimental error. By comparison, HPLC analysis of HbA (Fig. 7, bottom panel) showed that the normal β -chain eluted at 21.3 min (average of 2 determinations, ± 0.9 min) and the α -chain eluted at 27.9 min (average of 2 determinations, ± 1.5 min). Therefore, differences between the 2 components due to primary sequence or posttranslational changes were not evident by these analyses.

Table 5. Spectral properties of D99K(β) isoelectric focusing forms^a

Sample	Spectral ratio	
	272/539	420/539
HbA	2.64	14.4
D99K(β) (before isoelectric focusing)	2.69	14.8
D99K(β) (extracted)	2.67	14.5
D99K(β)-1	3.02	14.9
D99K(β)-2	2.70	14.4

^a The Hb are the CO derivatives. At absorbance values of 4.0 or less, the precision and accuracy of the values are within $\pm 1\%$.

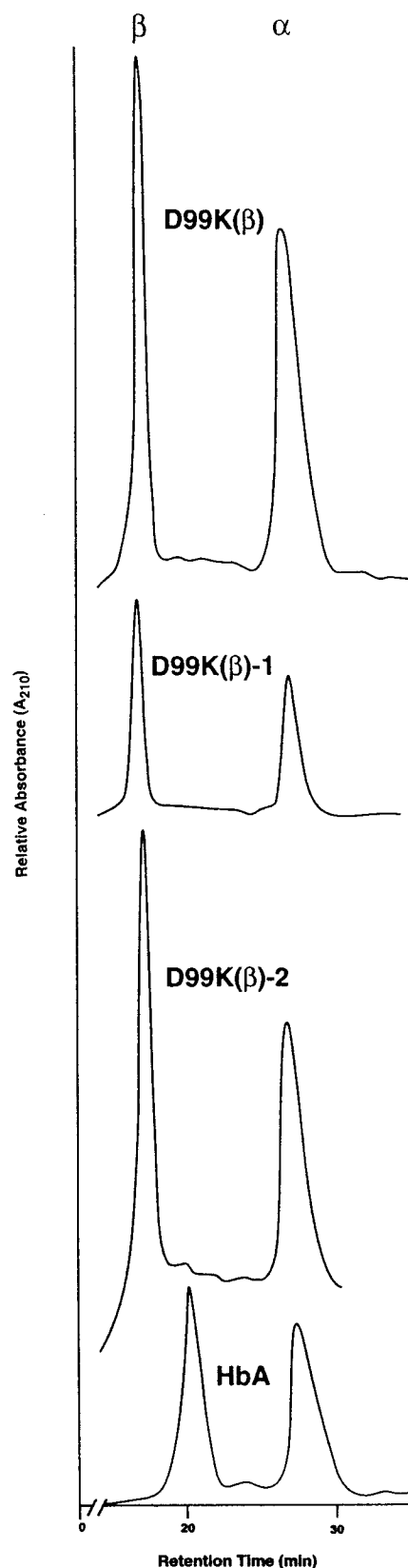


Fig. 7. Separation of α - and β -globin chains of D99K(β) mutant Hb. The D99K(β) and isolated D99K(β)-1 and 2 were chromatographed on a Vydac C-4 column as described in the text. The amounts of hemoglobin applied were in the range of 100–200 μ g.

Table 6. Mass spectrometric analysis of the 2 forms of the D99K(β) Hb mutant^a

Hb form	Mass					
	Heme		α -Globin		β -Globin	
	Measured	Calculated	Measured	Calculated	Measured	Calculated
D99K(β)-1	616.8	616.5	15,127.1	15,126.4	15,881.4	15,881.3
D99K(β)-2	616.6	616.5	15,124.4	15,126.4	15,879.6	15,881.3

^a The analyses for heme and globin masses were performed as described in the text. The precision for the globin measurements is ± 2.0 Da and for the heme measurements ± 0.5 Da.

The possibility that the different mobilities of D99K(β)-1 and D99K(β)-2 could be due to heme was evaluated below.

Mass spectrometric analysis of separated D99K(β)-1 and D99K(β)-2

In order to investigate the possibility that some subtle change (not detectable by HPLC analysis) could have occurred on the protein, the separated D99K(β)-1 and D99K(β)-2 were each subjected to matrix-assisted laser desorption mass spectrometric analysis. The results, which are shown in Table 6, indicate that the α - and β -subunits of D99K(β)-1 and D99K(β)-2 have identical masses within the error of the measurements (± 2 Da). The measured increase in mass of the mutant D99K(β)-1 and D99K(β)-2 chains over a normal β -chain were, respectively, 13.2 ± 2 Da and 11.4 ± 2 Da, values consistent with the increase of 13 Da calculated for the replacement of 1 aspartic acid by a lysine residue. The identical molecular masses of the 2 forms are consistent with identical primary structures and also indicate that modification during isoelectric focusing did not occur.

The possibility that yeast contains different types of heme moieties that could lead to the generation of the 2 D99K(β) recombinant mutant forms was evaluated by matrix-assisted laser desorption mass spectrometric analysis. The results, which are shown in Table 6, indicate that the heme moieties derived from D99K(β)-1 and D99K(β)-2 have masses that are identical within the accuracy of the measurement (± 0.5 Da), demonstrating that such a difference in the heme moieties is unlikely. Because the mass spectrometric results show that the primary sequence and the heme prosthetic group in the 2 forms of the D99K(β) recombinant mutant Hb are the same, the possibility was considered that there was some type of conformational difference between the 2 forms of the D99K(β) recombinant mutant as described next.

Circular dichroism spectra

The circular dichroic spectrum in the 200–300-nm range of the D99K(β) mutant prior to isoelectric focusing and the corresponding spectra of the 2 separate D99K(β)-1 and D99K(β)-2 indicated that the differences were insignificant (data not shown). However, in the Soret region at 410 nm, D99K(β)-1 displayed negative ellipticity, a feature absent in D99K(β)-2 (Fig. 8). The overall circular dichroism spectrum and positive ellipticity of D99K(β)-2 in the Soret region were practically identical to that of HbA. These results suggested that the heme-protein en-

vironment of D99K(β)-2 was closer to that of natural HbA than that of D99K(β)-1. In addition, the degree of ellipticity at 410 nm for the D99K(β) recombinant mutant as well as that at 345 nm before isoelectric focusing reflected the contributions of D99K(β)-1 and D99K(β)-2 at each wavelength. These observations are not consistent with artifact formation of these bands during isoelectric focusing, but the relationship between their electrophoretic behavior and circular dichroism properties is not known. In a separate study using a different sample of the D99K(β) Hb mutant from a different yeast preparation, circular dichroism results similar to those described in Figure 8 on the separated D99K(β)-1 and D99K(β)-2 bands were obtained.

Discussion

There are 8 known natural Hb mutants with substitutions at Asp-99(β) (Jones et al., 1967; Rucknagel et al., 1967; Reed et al., 1968; Bunn et al., 1974; Weatherall et al., 1977; Rochette et al., 1984; Tamagnini et al., 1991; Wajcman et al., 1991). In the absence of allosteric regulators, the oxygen binding curves of these natural mutants in dilute solution do not show cooperativity (n values near 1) and they have an increased oxygen affinity. Both properties have been attributed to the increased dissociation of the tetrameric state of these natural mutant Hb into dimers. As

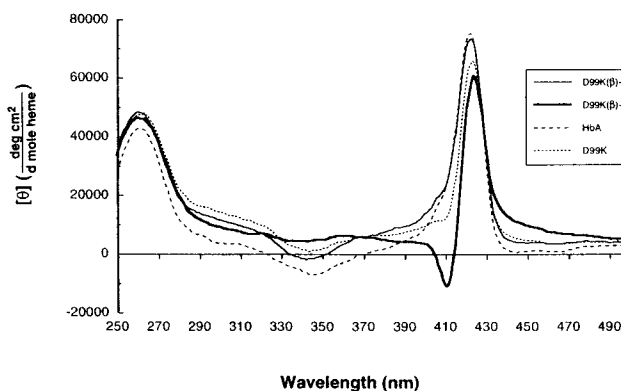


Fig. 8. Circular dichroism spectra of D99K(β) mutant Hb. The spectra were recorded at the concentration of approximately 30 μ M mutant Hb as the CO derivative and have been corrected for small differences in protein concentration. The D99K(β)-1 and D99K(β)-2 forms were isolated after isoelectric focusing, as described in the text. The measurements were made on unstained bands from the gel.

described in this communication, the D99K(β) mutant has a reduced but not absent cooperativity ($n = 2$) compared to that of normal Hb ($n = 3$). Our results using haptoglobin binding, light scattering, fluorescence quenching, and gel filtration indicate predominantly a dimeric structure for the D99K(β) mutant in either the oxygenated or deoxygenated state at concentrations in the range of 0.2 mM or less in heme. However, at the Hb concentration used for measurement of the oxygen dissociation curves (2–15 mM in heme), it is not known how much of the mutant Hb is tetrameric or dimeric because the 4 methods used above to measure the tetramer–dimer dissociation cannot be used at such high Hb concentrations. Existing procedures must be modified or novel ones devised for these measurements. However, the absence of large changes in oxygen affinity over the 8-fold change in Hb concentration suggests a preponderance of the dimeric structure.

Of particular interest is the lack of an effect of chloride and the marginal effect of the allosteric regulators 2,3-DPG or IHP on the oxygen equilibrium curve of the recombinant mutant Hb D99K(β) compared to HbA. This result may be due to the presence of dimeric Hb because a major mechanism by which chloride leads to a decreased oxygen affinity is by neutralizing positive charges in the 2,3-DPG cleft and in the central dyad axis (Chiancone et al., 1975; Nigen & Manning, 1975; Bonaventura et al., 1976; Bonaventura & Bonaventura, 1978; Manning et al., 1978; Nigen et al., 1980; Fronticelli et al., 1988; Vandegriff et al., 1989; Ueno & Manning, 1992; Perutz et al., 1993; Ueno et al., 1993). Both of these anion binding regions are hallmarks of the tetramer but are absent in the dimer. The importance of the central dyad axis in the control of oxygen affinity by chloride has recently been shown by structural studies comparing human and bovine Hb (Perutz et al., 1993) and chemical modification studies showing that both Hb had related functional chloride binding sites (Ueno & Manning, 1992; Ueno et al., 1993). Therefore, the lack of a chloride response in lowering the oxygen affinity is consistent with the absence of these quaternary features in the mutant Hb at the concentration studied. The marginal response to 2,3-DPG and IHP could be due either to the presence of some tetrameric Hb or to its generation in the presence of these effectors; further study is needed to clarify this point. The data indicate that the presence of equivalent amounts of the mutant Hb and HbA in a heterozygous erythrocyte would lead to a significant reduction in the amount of oxygen released even in the presence of allosteric regulators. Therefore, under physiological conditions, this mutant Hb in a red cell would likely be dysfunctional.

It is informative to compare the properties of the D99K(β) Hb mutant with the 2 recombinant mutants of Tyr-42(α), the site closely linked to Asp-99(β) at the $\alpha_1\beta_2$ subunit contact in deoxy Hb (see Kinemage 1). Imai et al. (1991) reported that recombinant mutants with phenylalanine or histidine substitutions at this position, Y42F(α) and Y42H(α), respectively, had an increased oxygen affinity and a decreased cooperativity, properties shared with the D99K(β) mutant. Of possible relevance to the findings in the present communication is the observation that the Y42H(α) mutant had an n value of 2 at pH 6.8, a value similar to that for D99K(β) reported here. At higher pH there was diminished yet measurable cooperativity for the Y42H(α) mutant. Imai et al. (1991) attributed the mild functional loss in the Y42H(α) mutant to the presence of a weak hydrogen bond formed in the deoxy state between His-42(α) and Asp-99(β) in

the mutant Hb. Whether there is any type of bonding between the protonated ϵ -NH₂ group of the mutant Lys-99(β) and any other side chains must await the solution of the crystal structure of the D99K(β) Hb mutant forms, which may also shed light on the source of its cooperativity. Vallone et al. (1993) have demonstrated the importance of other α -chain subunit contacts in the general region of the $\alpha_1\beta_2$ contact.

It is also possible that the introduction of a Lys residue has created a new chloride binding site, analogous to that recently reported by Rivetti et al. (1993) for Hb Rothschild (Trp-37(β) \rightarrow Arg). Studies on other recombinant Hb (Baudin et al., 1993) with substitutions in this region of the protein not found in natural Hb mutants will likely continue to reveal information on this important region of the Hb molecule.

Because of the choice of substitution site, the D99K(β) recombinant mutant shows a tendency to dimerize, whereas other recombinant Hb expressed in this expression system remain tetrameric under similar conditions. Indeed, most mammalian Hb are tetrameric, enabling them to interact efficiently with allosteric regulators. However, some dimeric Hb in the unliganded form, i.e., from the mollusc bivalve clams, show very similar negative and positive ellipticity in the region of the Soret band as found for the D99K(β)-1 Hb (Chiancone et al., 1981, 1990; Antonini et al., 1984; Bellelli et al., 1987). The interaction of the heme with 2 different environments of the adjacent globin may be responsible for generation of the D99K(β)-1 and D99K(β)-2 forms. Alternatively, the 2 forms could be related to the reports of a "disordered" heme environment in some monomeric Hb and in some myoglobins. Thus, La Mar and colleagues (Burns & La Mar, 1981), using NMR techniques, showed that the heme of tuna myoglobin has 2 different orientations present in a 60:40 ratio, similar to the distribution of the 2 forms of the D99K(β) mutant found in the present study. Cooke and Wright (1985) also reported a difference in heme orientation in the monomeric Hb of *Glycera*, and Constantini and Satterlee (1987) found that these forms were separable by isoelectric focusing. O'Connor et al. (1980) and Santucci et al. (1988) reported a correlation between heme orientation and circular dichroism in the Soret region of *Glycera* Hb. In their description of heme disorder in myoglobin, Light et al. (1987) showed a correlation between heme orientation and the degree of circular dichroic ellipticity in myoglobin. Of particular interest is the observation of Goodhall and Shooter (1969) that the negative ellipticity in the isolated β -chain of HbA in the Soret region is lost when tetrameric Hb is formed. On the other hand, there could be a protein conformational change that gives rise to the 2 forms of the D99K(β) mutant.

Other heme proteins that are homogeneous by other criteria also show 2 major bands on isoelectric focusing. Thus, Hull and Wharton (1993) showed that cytochrome oxidase/nitrite reductase, a protein shown to be pure by several criteria, had 2 bands separable by about 0.05–0.10 pH unit on isoelectric focusing. These 2 forms were interconvertible upon a subsequent isoelectric focusing, but the D99K(β) mutant Hb forms were not under such conditions. This difference could be a reflection of the homodimeric nature of cytochrome oxidase/nitrite reductase compared with the heterodimeric structure of the D99K(β) recombinant mutant at the concentrations used for the isoelectric focusing studies. Further studies are needed to elucidate the molecular basis for the existence of 2 forms of the mutant Hb and their relationship, if any, to the cooperativity of the mutant Hb.

Materials and methods

Reagents

The restriction endonucleases and other enzymes were from Boehringer Mannheim. The DNA sequencing kit and the T7 DNA polymerase (Sequenase, version 2.0) were obtained from U.S. Biochemicals. The oligonucleotide used to make the mutation had the sequence [5'-CTGAAGTTCTCAGGTTTCACG TGCAGCTTG-3'] and was purchased from Operon Technologies (Alameda, California). The underlined bases were used to produce the desired mutant.

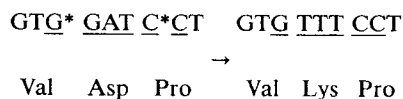
Bacterial and yeast strains and growth conditions

These strains have been described previously (Martin de Llano et al., 1993b). The yeast strains were grown in 10 culture flasks (2 L each) for 4 days in the presence of ethanol as the carbon source, and Hb expression was induced by the addition of 2% galactose for 24 h as described previously (Martin de Llano et al., 1993a, 1993b).

Site-directed mutagenesis

The plasmid pGS189 and pGS389 that contained the full-length human α - and β -globin cDNAs under transcriptional control of dual pGGAP promoters were used as gene sources. The 1.2-kb *Sph* I fragment containing the β -globin cDNA on pGS189 was inserted into the *Sph* I site on the replicative form of M13mp18, so that the phage contains the sense DNA strand of the β -globin gene. *Escherichia coli* BW 313 was transfected with the recombinant phage and the oligonucleotide described above was used to create the mutation $\beta 99\text{Asp} \rightarrow \text{Lys}$ by the method of Kunkel (1985).

The presence of the mutation was screened by loss of the *Bam* HI site, which cleaves at the GGATCC sites marked by asterisks:



Sequencing of the entire β -globin gene indicated that this was the only site of mutation. The mutated β -globin region was excised by *Sph* I digestion and subcloned back into the *Sph* I site of pGS189. The correct orientation of the recombinant fragment was confirmed by DNA sequencing. The plasmid pGS18999K was treated with *Not* I to release the cassette with the mutated globin gene, which was subsequently inserted into the expression vector pGS389 that had been digested with the same restriction enzyme. The correct orientation of the DNA fragment was again confirmed by DNA sequencing, and the recombinant plasmid was transformed into yeast GSY112 *cir*⁰ strain. Transformants were selected on a complete minimal agar plate without uracil.

Protein purification

Upon completion of growth, the yeast cells were saturated with CO gas, collected, broken by homogenization in a Bead-Beater, as described previously (Martin de Llano et al., 1993a, 1993b). The initial purification step was achieved on carboxymethyl-cellulose (Whatmann, CM-52) and the final purification on

HPLC employed the same Synchropak CM 300 (250 \times 10 mm) column used previously (Martin de Llano et al., 1993a, 1993b). However, with this mutant Hb, a different gradient was employed because of its more basic properties compared with HbA. The gradient, which consisted of 10 mM potassium phosphate buffer, pH 5.85, and 22.5 mM potassium phosphate buffer, pH 8.0 (150 mL of each), was from 20% to 85% buffer B over 10 min, from 85% to 100% buffer B over 60 min, and then 20 min of buffer B alone at a flow of 2.5 mL/min (A = 30 mM bis-Tris, 30 mM sodium acetate, 1 mM EDTA, pH 6.4; B = 30 mM bis-Tris, 150 mM sodium acetate, 1 mM EDTA, pH 6.4).

Analytical procedures

SDS-PAGE was performed on the recombinant D99K(β) mutant, as described previously (Martin de Llano et al., 1993b). Electrophoresis of native proteins was done on the Beckman Paragon system. Globin chains were separated by HPLC on a Vydac C-4 column (250 \times 4.6 mm) using a gradient from 0.1% TFA to 80% acetonitrile in 0.1% TFA. Amino acid analysis of globin chains isolated by this procedure was performed on a Beckman 6300 instrument with System Gold data handling system. Tryptic peptide mapping was performed on the reduced, carboxymethylated globin chains, as described previously (Martin de Llano et al., 1993a). However, the gradient used for separation of the tryptic peptides of the mutant β -chain was changed to 0% to 15% B over 10 min, 15% to 55% B over 60 min, and then 55% to 100% B over 10 min (A = 0.1% TFA; B = 80% acetonitrile, 0.1% TFA). Sequencing of the isolated peptide was performed on an Applied Biosystem gas-phase sequencer. Spectra were recorded on a Cary 2200 spectrophotometer.

Mass spectrometry analysis

Hb samples were subjected to mass spectrometric analysis on a matrix-assisted laser desorption time-of-flight mass spectrometer constructed at The Rockefeller University and described elsewhere (Beavis & Chait, 1989, 1990). The mass spectra were acquired by adding the individual spectra of 200 laser shots. Hb samples isolated from the isoelectric focusing gels but not stained with a dye were prepared for laser desorption mass analysis as follows: the laser desorption matrix material (4-hydroxy- α -cyano-cinnamic acid) was dissolved in formic acid/water/isopropanol 1:6:4 (v/v/v) (50 mM). A 10 mM potassium phosphate solution (pH 8) containing the Hb sample was then added to the matrix solution to give a final concentration of the Hb of approximately 2 μM . A small aliquot (0.5 μL) of this mixture was applied to the metal probe tip and dried at room temperature with forced air. The sample was then inserted into the mass spectrometer and analyzed. Horse heart myoglobin and, after confirmation of its molecular weight, Hb α -chain were used to calibrate the mass spectra.

Determination of tetrameric and dimeric Hb

By binding to haptoglobin

Separation of the Hb tetramer (64 kDa) from the haptoglobin-bound dimer (132 kDa) was achieved by use of a Centricon 100 filter. Haptoglobin-bound dimer remained in the retentate, whereas free Hb tetramer passed through the membrane. The

concentration of the Hb was determined spectrophotometrically before and after the filtration process. Haptoglobin ($1 \mu\text{M}$) was mixed with oxy Hb or deoxy Hb ($2 \mu\text{M}$ in heme) in 0.1 M potassium phosphate, pH 7.0, at ambient temperature. The mixture was then filtered through a Centricon 100 concentrator (Amicon) by centrifugation at $1,000 \times g$ for 10 min; concentrations of $50 \mu\text{M}$ Hb or higher could not be filtered. For deoxy Hb, anaerobic conditions were achieved by addition of 9 mM sodium dithionite to both the Hb and the haptoglobin solutions before they were mixed. After filtration through the Centricon 100, the spectrum of the deoxy Hb sample showed that the Hb remained deoxygenated throughout the filtration process.

By quenching of haptoglobin fluorescence

Equivalent concentrations of oxy and deoxy Hb (2.0 – $8.0 \mu\text{M}$ in heme) were mixed with $1 \mu\text{M}$ haptoglobin, and the decrease in fluorescence (Nagel & Gibson, 1967) was measured on a Hitachi Perkin-Elmer MPF-2A fluorescence spectrophotometer using an excitation wave of 287 nm and an emission wave of 350 nm . Anaerobic conditions were achieved by bubbling the Hb solution in a sealed cuvette with water-saturated N_2 for 2 min prior to addition of dithionite (0.20 mM) and a haptoglobin solution containing 0.20 mM dithionite. After incubation for $\sim 2 \text{ min}$, the fluorescence value was determined. The spectra of the deoxy samples indicated that the Hb had remained in the deoxy state during the fluorescence measurement.

By gel filtration

This procedure was only performed with oxygenated Hb. A column of Sephadex G-75 ($0.9 \times 60 \text{ cm}$) in 50 mM bis-Tris acetate, pH 7.5, was eluted at a flow rate of 0.2 mL/min . The Hb samples were applied in a volume of about $100 \mu\text{L}$.

By light scattering

Solutions of oxygenated HbA or D99K(β) mutant (ca. 2 mL , 0.2 mM in heme) in 0.1 M KCl were analyzed on a Biotage molecular size detector (model dp-801).

Determination of oxygen binding curves

For the recombinant and natural Hb (ca. 2 – 15 mM [heme] of each in 50 mM bis-Tris acetate, pH 7.5 at 37°C), the oxygen binding curves were measured on a modified Hem-O-Scan (Martin de Llano et al., 1993a); the tank containing the oxygenating gas had $25\% \text{ O}_2$. Just prior to this analysis, the CO form of Hb, the ligand state in which the mutant Hb was purified to ensure that the heme was not oxidized, was converted to the oxy form by several exposures to incandescent light in an atmosphere of $100\% \text{ O}_2$, as described previously (Manning, 1981). This conversion was considered complete when the A_{540}/A_{560} ratio was 1.7.

To measure the effect of anions on the oxygen affinity of the D99K(β) mutant Hb, an aliquot of a solution of 2.5 M NaCl or 5 mM 2,3-DPG in 50 mM bis-Tris acetate, pH 7.5, was added to the Hb sample to achieve the desired final concentration and the P_{50} was again measured at 37°C .

Isoelectric focusing

The Hb-Resolve system from Isolabs, which employs a pH gradient, from pH 6 to 8, was used. After staining and destaining

(Martin de Llano et al., 1993a, 1993b) scanning and integration of the gel bands after staining with 0.2% bromophenol blue were achieved on a Gilford model 250 spectrophotometer with a Shimadzu model CR6A integrator attached. In some studies, the separated isoelectric focusing bands were eluted from the agarose gel after cutting them separately with a razor blade and immersing them in 1 mL of CO-saturated 50 mM bis-Tris-acetate, pH 7.5. After being kept overnight on ice, the extracted Hb were recovered after centrifugation at $4,500 \text{ rpm}$ with an Amicon Centricon in a refrigerated Sorvall RC-2B centrifuge.

Circular dichroism measurements

The CD spectra of HbA, the D99K(β) recombinant mutant, and the 2 separate bands found during isoelectric focusing were measured on an Aviv 62DS CD spectrometer equipped with a temperature controller. The instrument was calibrated with a 2-point calibration method using (+)-10-camphorsulfonic acid. Measurements were made at 20°C and in 1-cm quartz cells on 2 different samples each of HbA, of unfractionated D99K(β) mutant Hb, and of the separate D99K(β)-1 and D99K(β)-2 forms. Wavelength scans were performed from 500 to 250 nm , digitized at 1-nm intervals, and signal-averaged with a 4-s time constant. The data were corrected for any baseline changes, smoothed, and normalized to units of molar ellipticity on a heme basis. After the analysis, the absorption spectra of the samples were recorded and their concentrations were determined by amino acid analysis after acid hydrolysis.

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References

- Antonini E, Ascoli F, Brunori M, Chiancone E, Verzili D, Morris RJ, Gibson QH. 1984. Kinetics of ligand binding and quaternary conformational change in the homodimeric hemoglobin from *Scapharca inaequivalvis*. *J Biol Chem* 259:6730–6738.
- Baudin V, Paginier J, Kiger L, Kister J, Schaad O, Bihoreau MT, Lacaze N, Marden MC, Edelstein SJ, Poyart C. 1993. Functional consequences of mutations at the allosteric interface in hetero- and homo-hemoglobin tetramers. *Protein Sci* 2:1320–1330.
- Beavis RC, Chait BT. 1989. Factors affecting the ultraviolet laser desorption of proteins. *Rapid Commun Mass Spectrom* 3:233–237.
- Beavis RC, Chait BT. 1990. High-accuracy molecular mass determination of proteins using matrix-assisted laser desorption mass spectrometry. *Anal Chem* 62:1836–1840.
- Bellelli A, Foon R, Ciscoli F, Brunori M. 1987. Heme disorder in two myoglobins: Comparison of reorientation rate. *Biochem J* 246:787–789.
- Benesch RE, Ikeda S, Benesch R. 1976. Reaction of haptoglobin with hemoglobin covalently cross-linked between $\alpha\beta$ dimers. *J Biol Chem* 251:465–470.
- Blouquit Y, Braconnier F, Galacteros F, Arous N, Soria J, Zittoun R, Rosa J. 1981. Hemoglobin Hotel-Dieu. A new abnormal hemoglobin with high oxygen affinity. *Hemoglobin* 5:19–31.
- Bonaventura C, Bonaventura J. 1978. Anionic control of hemoglobin function. In: Caughey WS, ed. *Biochemical and clinical aspects of hemoglobin abnormalities*. New York: Academic Press. pp 647–663.
- Bonaventura J, Bonaventura C, Sullivan B, Ferruzzi G, McCurdy PR, Fox J, Moo-Pen WF. 1976. Hemoglobin Providence. *J Biol Chem* 251:7563–7571.

- Bunn HF, Wohl RC, Bradley TB, Cooley M, Gibson QH. 1974. Functional properties of hemoglobin Kempsey. *J Biol Chem* 249:7402-7409.
- Burns PD, La Mar GN. 1981. Characterization of conformational heterogeneity in the heme pocket of ferricytochrome c using high field proton nuclear magnetic resonance spectroscopy. *J Biol Chem* 256:4934-4939.
- Chiancone E, Nørne JE, Forsen S, Bonaventura J, Brunori M, Antonini E, Wyman J. 1975. Identification of chloride-binding sites in hemoglobin by nuclear-magnetic-resonance quadrupole-relaxation studies of hemoglobin digests. *Eur J Biochem* 55:385-390.
- Chiancone E, Vecchini P, Verzili D, Ascoli F, Antonini E. 1981. Dimeric and tetrameric hemoglobins from the mollusc *Scapharca inaequivalvis*: Structural and functional properties. *J Mol Biol* 152:577-592.
- Chiancone E, Verzili D, Boffi A, Royer WE Jr, Hendrickson WA. 1990. A cooperative hemoglobin with directly communicating hemes: The *Scapharca inaequivalvis* homodimer. *Biophys Chem* 37:287-292.
- Constantinidis I, Satterlee JD. 1987. Isoelectric focusing purity criteria and ¹H NMR detectable spectroscopic heterogeneity in the major isolated monomer hemoglobins from *Glycera dibranchiata*. *Biochemistry* 26:7779-7786.
- Cooke RM, Wright PE. 1985. Heme orientation in the major monomeric hemoglobins of *Glycera dibranchiata*. *Biochim Biophys Acta* 832:365-372.
- Doyle ML, Lew G, Turner GJ, Rucknagel D, Ackers GK. 1992. Regulation of oxygen affinity by quaternary enhancement: Does hemoglobin Ypsilanti represent an allosteric intermediate? *Proteins Struct Funct Genet* 14:351-362.
- Fronticelli C, Bucci E, Razynska A. 1988. Modulation of oxygen affinity in hemoglobin by solvent components. Interaction of bovine hemoglobin with 2,3-diphosphoglycerate and monatomic anions. *J Mol Biol* 202:343-348.
- Goodhall PT, Shooter EM. 1969. Changes in heme environment due to subunit interaction in hemoglobin. *J Mol Biol* 39:675-678.
- Hull HH, Wharton DC. 1993. Isoelectrophoretic characterization of *Pseudomonas* cytochrome oxidase/nitrite reductase and its heme d₁-containing domain. *Arch Biochem Biophys* 301:85-90.
- Imai K, Fushitani K, Miyazaki G, Ishimori K, Kitagawa T, Wada Y, Morimoto H, Morishima I, Shih DTB, Tame J. 1991. Site-directed mutagenesis in haemoglobin: Functional role of tyrosine-42(C7) α at the α 1- β 2 interface. *J Mol Biol* 218:769-778.
- Jones RT, Osgood EE, Brimhall B, Koler RD. 1967. Hemoglobin Yakima. Clinical and biochemical studies. *J Clin Invest* 46:1840-1847.
- Kunkel TA. 1985. Rapid and efficient site-specific mutagenesis without phenotypic selection. *Proc Natl Acad Sci USA* 82:488-492.
- Light WR, Rohlf RJ, Palmer G, Olson JS. 1987. Functional effects of heme orientational disorder in sperm whale myoglobin. *J Biol Chem* 262:46-52.
- Manning JM. 1981. Preparation of hemoglobin carbamylated at specific NH₂-terminal residues. *Methods Enzymol* 76:159-167.
- Manning JM, Nigen AM, Charache S, Alben JO. 1978. Major sites for the oxygen-linked binding of chlorine to hemoglobin. In: Caughey WS, ed. *Biochemical and clinical aspects of hemoglobin abnormalities*. New York: Academic Press. pp 687-694.
- Martin de Llano JJ, Jones W, Schneider K, Chait BT, Rodgers G, Benjamin LJ, Weksler B, Manning JM. 1993a. Biochemical and functional properties of recombinant human sickle hemoglobin expressed in yeast. *J Biol Chem* 268:27004-27011.
- Martin de Llano JJ, Schneewind O, Stetler G, Manning JM. 1993b. Recombinant human sickle hemoglobin expressed in yeast. *Proc Natl Acad Sci USA* 90:918-922.
- Nagel RL, Gibson QH. 1967. Kinetics and mechanism of complex formation between hemoglobin and haptoglobin. *J Biol Chem* 242:3428-3434.
- Nigen AM, Manning JM. 1975. The interaction of anions with hemoglobin carbamylated on specific NH₂-terminal residues. *J Biol Chem* 250:8248.
- Nigen AM, Manning JM, Alben JO. Oxygen-linked binding sites for inorganic anions to hemoglobin. 1980. *J Biol Chem* 255:5525-5529.
- O'Connor ERP, Harrington JP, Herskovits TT. 1980. Solution studies on heme proteins. *Biochim Biophys Acta* 624:346-362.
- Perutz M. 1990. *Mechanisms of cooperativity and allosteric regulation in proteins*. New York: Cambridge University Press.
- Perutz MF, Fermi G, Poyart C, Pagnier J, Kister J. 1993. A novel allosteric mechanism in haemoglobin: Structure of bovine deoxyhaemoglobin, absence of specific chloride-binding sites and origin of the chloride-linked Bohr effect in bovine and human haemoglobin. *J Mol Biol* 233:536.
- Perutz MF, Ten Eyck LF. 1971. Stereochemistry of cooperative effects in hemoglobin. *Cold Spring Harbor Symp Quant Biol* 36:295-310.
- Reed CS, Hampson R, Gordon S, Jones RT, Novy MJ, Brimhall B, Edwards EJ, Koler RD. 1968. Erythrocytosis secondary to increased oxygen affinity of a mutant hemoglobin. Hemoglobin Kempsey. *Blood* 31:623-632.
- Rivetti C, Mozzarelli A, Rossi GL, Kwiatkowski LD, Wierzbica AM, Noble RW. 1993. Effect of chloride on oxygen binding to crystals of hemoglobin Rothschild (β 37Trp \rightarrow Arg) in the T quaternary structure. *Biochemistry* 32:6411-6418.
- Rochette J, Poyart C, Varet B, Wajcman H. 1984. A new hemoglobin variant, the α 2 β 2(99) G1 Asp \rightarrow Val. *FEBS Lett* 166:8-12.
- Rucknagel DL, Glynn KP, Smith JR. 1967. Hemoglobin Ypsilanti characterized by increased oxygen affinity, abnormal polymerization and erythremia. *Clin Res* 15:270.
- Santucci R, Mintorovitch J, Constantinidis I, Satterlee JD, Ascoli CD. 1988. Studies on the reversed heme orientation in monomeric *Glycera dibranchiata* hemoglobins. *Biochim Biophys Acta* 953:201-204.
- Tamagnini GP, Ribeiro ML, Valente V, Ramachandran M, Wilson JB, Baysal E, Gu LH, Huisman THJ. 1991. Hb Coembra or α 2 β 2 99(G1) Asp \rightarrow Glu, a newly discovered high oxygen affinity variant. *Hemoglobin* 15:487-496.
- Turner BW, Pettigrew DW, Ackers GK. 1981. Measurement and analysis of ligand-linked subunit dissociation equilibria in human hemoglobins. *Methods Enzymol* 76:596-628.
- Turner GJ, Galacteros F, Doyle ML, Hedlund B, Pettigrew DW, Turner BW, Smith FR, Moo-Penn W, Rucknagel DW, Ackers GK. 1992. Mutagenic dissection of hemoglobin cooperativity: Effects of amino acid alteration on subunit assembly of oxy and deoxy tetramers. *Proteins Struct Funct Genet* 14:333-350.
- Ueno H, Manning JM. 1992. The functional, oxygen-linked chloride binding sites of hemoglobin are contiguous within a channel in the central cavity. *J Protein Chem* 11:177-185.
- Ueno H, Popowicz A, Manning JM. 1993. Random chemical modification of the oxygen-linked chloride binding sites of hemoglobin: Those in the central dyad axis influence the transition between deoxy and oxy hemoglobin. *J Protein Chem* 12:561-570.
- Vallone B, Vecchini P, Cavalli V, Brunori M. 1993. Site-directed mutagenesis in hemoglobin. Effect of some mutations at protein interfaces. *FEBS Lett* 324:112-117.
- Vandegriff KD, Medina F, Marini MA, Winslow RM. 1989. Equilibrium oxygen binding to human hemoglobin cross-linked between the α chains by bis(3,5-dibromosalicyl) fumarate. *J Biol Chem* 264:17824-17833.
- Wagenbach M, O'Rourke K, Vitez L, Wiczorek A, Hoffmann S, Durfee S, Tedesco J, Stetler G. 1991. Synthesis of wild-type and mutant human hemoglobins in *Saccharomyces cerevisiae*. *Biotechnology* 9:57-61.
- Wajcman H, Kister J, Vasseur C, Blouquit Y, Behnken JL, Galacteros F. 1991. Hb Ingelheim. A new high affinity hemoglobin variant destabilizing the α 1 β 2 interface. *Blood* 78(Suppl 1):206a.
- Weatherall DJ, Clegg JB, Callender ST, Wells RMG, Gale RE, Huehns ER, Perutz MF, Viggiano G, Ho C. 1977. Hemoglobin Radcliffe. A high affinity variant causing familial polycythaemia. *Br J Haematol* 35:177-191.