

COMMONWEALTH OF AUSTRALIA

PATENTS ACT 1952

DECLARATION IN SUPPORT OF A CONVENTION
APPLICATION FOR A PATENT

In support of the convention application made for a patent for an invention entitled:

Blood Substitutes

I, Martin Richard Wood, of Medical Research Council of 20 Park Crescent, London WIN 4AL, United Kingdom, do solemnly and sincerely declare as follows:

1. I am authorised by Medical Research Council, one of the applicants for the patent, to make this declaration on its behalf.
2. The basic application as defined by Section 141 of the Act was made in United Kingdom on 16 May 1987 by Medical Research Council.
3. Stephen J. Hoffmann of 2090 Albion Street, Denver, Colorado 80207, United States of America and Kiyoshi Nagai, of 19 Mulberry Close, Cambridge CB4 2AS, United Kingdom, are the actual inventors of the invention and the facts upon which the applicants are entitled to make the application are as follows:

Somatogenetics International, Inc. was entitled to the share in the invention vesting in Stephen J Hoffman by virtue of an employment agreement between Stephen J Hoffman and his employer, Somatogenetics International, Inc.; Medical Research Council was entitled to the share in the invention vesting in Kiyoshi Nagai by virtue of an employment agreement between Kiyoshi Nagai and his employer, Medical Research Council; Somatogenetics International, Inc. and Medical Research Council agreed to make such assignments as would leave each of Somatogenetics International, Inc. and Medical Research Council with a one-half interest in and to the invention.

4. The basic application referred to in paragraph 2 of this Declaration was the first application made in a Convention country in respect of the invention the subject of the application.

DECLARED at London this 2nd day of May 1991

.....
Martin Richard Wood

TO: THE COMMISSIONER OF PATENTS
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(57) Claim

1. A method of supplementing the oxygen-carrying capacity of a patient's blood which comprises administering to the patient a nontoxic composition comprising a cell-free mutant hemoglobin.

24. A method of producing hemoglobin which comprises (a) producing alpha globin by (i) introducing a recombinant DNA molecule according to claim 19 into a suitable host other than an erythrocyte, (ii) expressing alpha globin as part of a fusion protein, (iii) cleaving said fusion protein at a selective cleavage site to liberate the alpha globin, and (iv) recovering and purifying said alpha globin; (b) obtaining beta globin from a source other than blood; and (c) preparing hemoglobin by combining said alpha and beta globin and a source of heme.



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Solutions of mutant hemoglobins having a lower oxygen affinity than that of native hemoglobin are used as blood substitutes. The mutant hemoglobins are preferably obtained by recombinant DNA techniques. Both alpha and beta globin chains can now be so prepared, making possible the production of wholly artificial hemoglobin, whether conventional or mutant in form. Solutions of wholly artificial hemoglobins are also used as blood substitutes.

BLOOD SUBSTITUTES

BACKGROUND OF THE INVENTION

Field of Invention

This invention relates to novel hemoglobin compositions useful as substitutes for red blood cells, and to methods of preparing same. It further relates to the preparation, using recombinant DNA technology, of mutant hemoglobins for use in such compositions.

Information Disclosure Statement

It is not always practical to transfuse a patient with donated blood. In these situations, use of a red blood cell substitute is necessary. The product must effectively transport O₂, just as do red blood cells. ("Plasma expanders", such as dextran and albumin, do not transport oxygen.) The two types of substitutes that have been studied most extensively are hemoglobin solutions and fluorocarbon emulsions.

Hemoglobin (Hgb) is the oxygen-carrying component of blood. Hemoglobin circulates through the bloodstream inside small enucleate cells called erythrocytes (red blood cells). Hemoglobin is a protein constructed from four associated polypeptide chains, and bearing prosthetic groups known as hemes. The erythrocyte helps maintain hemoglobin in its reduced, functional form. The heme iron atom is liable to oxidation, but may be reduced again by one of two enzyme systems within the erythrocyte, the cytochrome b₅ and glutathione reduction systems.

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Hemoglobin exhibits cooperative binding of oxygen by the four subunits of the hemoglobin molecule (two alpha-globins and two beta-globins in the case of Hgb A), and this cooperativity greatly facilitates efficient oxygen transport. Cooperativity, achieved by the so-called heme-heme interaction, allows hemoglobin to vary its affinity for oxygen. Hemoglobin reversibly binds up to four moles of oxygen per mole of Hgb. At high oxygen concentration, such as that found in the lungs, the oxygen affinity is high and hemoglobin is almost saturated with oxygen. At low oxygen concentration, such as that found in actively respiring tissue, the oxygen affinity is lowered and oxygen is unloaded.

Oxygen-carrying compounds are frequently compared by means of a device known as an oxygen dissociation curve. This curve is obtained when, for a given oxygen carrier, oxygen saturation is graphed against the partial pressure of oxygen. The percentage of saturation increases with partial pressure according to a sigmoid relationship. The P_{50} is the partial pressure at which the oxygen-carrying solution is half saturated with oxygen. It is thus a measure of oxygen-binding affinity; the higher the P_{50} , the more loosely the oxygen is held.

When the oxygen dissociation curve of a oxygen-carrying solution is such that the P_{50} is less than that for whole blood, it is said to be "left-shifted."

The oxygen affinity of hemoglobin is lowered by the presence of 2,3-diphosphoglycerate (2,3-DPG), chloride ions and hydrogen ions. Respiring tissue

releases carbon dioxide into the blood and lowers its pH (i.e. increases the hydrogen ion concentration), thereby causing oxygen to dissociate from hemoglobin and allowing it to diffuse into individual cells.

5

The ability of hemoglobin to alter its oxygen affinity, increasing the efficiency of oxygen transport around the body, is dependent on the presence of the metabolite 2,3-DPG. Inside the erythrocyte 2,3-DPG is present at a concentration nearly as great as that of hemoglobin itself. In the absence of 2,3-DPG "conventional" hemoglobin binds oxygen very tightly and would release little oxygen to respiring tissue.

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Aging erythrocytes release small amounts of free hemoglobin into the blood plasma where it is rapidly bound by the scavenging protein haptoglobin. The hemoglobin-haptoglobin complex is removed from the blood and degraded by the spleen and liver.

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It is clear from the above considerations that free native hemoglobin A, injected directly into the bloodstream, would not support efficient oxygen transport about the body. The essential allosteric regulator 2,3-DPG is not present in sufficient concentration in the plasma to allow hemoglobin to release much oxygen at venous oxygen tension, and free hemoglobin would be rapidly inactivated as an oxygen carrier by auto-oxidation of the heme iron.

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Nonetheless, solutions of conventional hemoglobin have been used as RBC substitutes. The classic method of preparing hemoglobin solutions employs outdated blood. The red cells are lysed and cellular debris is

removed, leaving what is hopefully "stromal-free hemoglobin" (SFH).

5 Several basic problems have been observed with this approach. The solution must be freed of any toxic components of the red cell membrane without resorting to cumbersome and tedious procedures which would discourage large-scale production. DeVenuto, "Appraisal of Hemoglobin Solution as a Blood
10 Substitute", Surgery, Gynecology and Obstetrics, 149: 417-436 (1979).

Second, as expected, such solutions are "left-shifted" (lower P_{50}) as compared to whole blood.
15 Gould, et al., "The Development of Polymerized Pyridoxylated Hemoglobin Solution as a Red Cell Substitute", Ann. Emerg. Med. 15: 1416-1419 (Dec. 1986).

20 Third, SFH has a half-life in the circulatory system of only about 2-4 hours. This is because oxyHgb partially dissociates into a dimer that is small enough to be filtered by the kidney.

25 Finally, SFH has a high colloid osmotic pressure (COD). Thus, administration of SFH in a dose that would have the same oxygen-carrying capacity as a unit of packed red blood cells is inadvisable, since the high osmotic pressure (60mm Hg) would cause a massive
30 influx of water from the cells into the bloodstream, thus dehydrating the patient's tissues. This consideration limits the dose of SFH to about 6-8 gm Hgb/dl.

In an effort to restore the desired P_{50} , researchers added 2,3-DPG to the hemoglobin solution. Unfortunately, 2,3-DPG was rapidly eliminated from the circulation. Scientists then turned to other organic phosphates, particularly pyridoxal phosphate. Like 2,3-DPG, these compounds stabilized the "T state" of the Hgb by forming a salt bridge between the N-termini of the two beta chains. The pyridoxylated hemoglobin had a P_{50} of 20-22 torr, as compared to 10 torr for SFH and 28 torr for whole blood. While this is an improvement over SFH, the pyridoxylated Hgb remains "high affinity" relative to whole blood.

Hemoglobin has been chemically modified (by intramolecular or intermolecular crosslinking) to increase intravascular retention and reduce osmotic pressure. Unfortunately, this polymerization also causes a "left shift" of the molecule's oxygen dissociation curve. Thus, for polymerized-pyridoxylated Hgb, the P_{50} is about 18 torr.

For chemical modifications of hemoglobin, See Iwashita, U.S. 4,412,989 and 4,301,144 (with polyalkylene glycol), Iwasaki, U.S. 4,670,417 (with polyalkylene oxide), (with a polysaccharide); Nicolau, U.S. 4,321,259 and U.S. 4,473,563 (with inositol phosphate); Wong, U.S. 4,710,488 and 4,650,786 (with inositol phosphate and a polysaccharide); Bonhard, U.S. 4,336,248 (with other proteins or gelatin derivatives); Walder, U.S. 4,598,064 and U.S. 4,600,531 (intramolecularly crosslinked hemoglobin) and Ajisaka, U.S. 4,377,512 (with inulin).

The human alpha- and beta-globin genes have both been cloned and sequenced. Liebhaber, et al., P.N.A.S.

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(U.S.A.) 77: 7054-58 (1980) (alpha-globin genomic DNA); Marotta, et al., J. Biol. Chem., 252: 5040-53 (1977) (beta-globin cDNA).

5 Nagai and Thorgerson (Nature, 309: 810-812, 1984) expressed in E. coli a hybrid protein consisting of the 31 amino-terminal residues of the lambda cII protein, an Ile-Glu-Gly-Arg linker, and the complete human beta globin chain. They cleaved the hybrid at the single
10 arginine with blood coagulation factor Xa, thus liberating the beta-globin chain.

 Later, Nagai, et al., P.N.A.S. (U.S.A.), 82: 7252-55 (1985) took the rDNA-derived human beta globin,
15 naturally derived human alpha globin, and a source of heme and succeeded in producing active human hemoglobin. Additionally, they produced two semi-artificial analogues of the naturally occurring mutant hemoglobins Hb Nympheas and Hb Daphne by site-directed
20 mutagenesis of the cloned beta-globin gene, expression of the modified gene, and combination of the rDNA-derived beta chain with naturally occurring alpha chain and a source of heme. Like the naturally occurring mutants, these semiartificial analogues exhibited
25 increased oxygen affinity as compared to "normal" hemoglobin. In subsequent studies, the structural basis for this change in oxygen binding was established. Iuisci and Nagai, Nature, 320: 555-56 (1986); and cp. Nagai, et al., Nature, 329: 858-860
30 (Oct. 1987) (similar production of mutant hemoglobins with replacements of Val(67beta)E11).

 Surprisingly, the expression of the human alpha globin gene in heterologous cells has not been
35 reported. Indeed, merely substituting the alpha globin

gene for the beta globin gene in the E. coli expression system of Nagai, et al. results in negligible expression of the lambda cII protein/alpha-globin fusion. It appears that there is something about the native alpha globin mRNA sequence which interferes with efficient translation in a bacterial host.

SUMMARY OF THE INVENTION

We have discovered that the disadvantages of hemoglobin solutions as blood substitutes are overcome if a mutant hemoglobin species is selected which, in a typical cell-free blood substitute solution, would impart to the solution a P_{50} comparable to that of non-mutant hemoglobin in RBC-bound state. Naturally occurring hemoglobin mutants which, in the erythrocyte environment, would impart to the erythrocyte a P_{50} higher than the normal value for whole blood (28 torr) are of particular interest, both in their own right and for what they teach about the structural foundations of oxygen affinity. It is expected that many such "right-shifted" species, outside the erythrocyte environment (and thus the right-shifting influence of 2,3-DPG), will assume a P_{50} comparable to or greater than that of the normal P_{50} for whole blood.

According to a first embodiment of this invention, there is provided a method of supplementing the oxygen-carrying capacity of a patient's blood which comprises administering to the patient a nontoxic composition comprising a cell-free mutant hemoglobin.

According to a second embodiment of this invention, there is provided a nontoxic pharmaceutical composition comprising a non-naturally occurring mutant hemoglobin in a pharmaceutically acceptable carrier.

According to a third embodiment of this invention, there is provided a recombinant DNA molecule comprising a fused gene, said fused gene comprising a first nucleotide sequence which codes on expression for an alpha globin, and a second nucleotide sequence which codes on expression for at least a 10 amino acid segment of a beta globin.

According to a fourth embodiment of this invention, there is provided a method of producing hemoglobin which comprises (a) producing alpha globin by (i) introducing a recombinant DNA molecule according to claim 19 into a suitable host other than an erythrocyte, (ii) expressing alpha globin as part of a fusion protein, (iii) cleaving said fusion protein at a selective cleavage site to liberate the alpha globin, and (iv) recovering and purifying said alpha globin; (b) obtaining beta globin from a source other



than blood; and (c) preparing hemoglobin by combining said alpha and beta globin and a source of heme.

According to a fifth embodiment of this invention, there is provided a hemoglobin composition comprising cell-free, biologically functional, wholly artificial, non-pyridoxylated hemoglobin in a pharmaceutically acceptable carrier, said hemoglobin being derived from transformed non-erythrocyte cells and said composition being absolutely free of erythrocyte membrane components other than hemoglobin.

According to an sixth embodiment of this invention, there is provided a non-naturally occurring low affinity hemoglobin mutant selected from the group consisting of mutants having the mutation hereinafter identified and combinations thereof.

According to a seventh embodiment of this invention, there is provided a hemoglobin composition comprising a solution of cell-free, mutant wholly artificial hemoglobin in a pharmaceutically acceptable carrier, said solution have a P_{50} under standard physiological conditions of 24-32 torr.

For the purposes of this invention, the term "conventional hemoglobin A" refers to the species of Hgb A whose alpha and beta chains are of the amino acid sequence given in Figure 1. This is the species which is most frequently found in human erythrocytes and which imparts to such erythrocytes a P_{50} of about 28 torr. A "hemoglobin A mutant" is defined as any species of hemoglobin A whose alpha or beta chain is of an amino acid sequence different from that set forth in



Figure 1. A "low affinity" hemoglobin A mutant is one which has a P_{50} at least about 10% greater than that of "conventional hemoglobin A" in the same environment. It is particularly desirable that its P_{50} be at least that twice of conventional (wild type) hemoglobin A in the absence of 2,3-DPG. A "recombinant" hemoglobin is one composed of an alpha and beta globin at least one of which is obtained by expression of a globin gene carried by a recombinant DNA molecule, whether the hemoglobin is a conventional hemoglobin or a mutant species.

A large number of naturally occurring low affinity Hgb A mutants are known. (See Table I). The mutations may appear in either the alpha or the beta chains of the molecule (or both, of course). Thus, Hgb Hazebrouck is a beta mutant (38(C4):thr->pro) whose P_{50} is 36 (in whole blood), declining to 27-29 torr in vitro.

Clearly, one cannot depend on nature to provide an adequate supply of these low affinity mutants. Consequently, the mutant polypeptide chain will usually be prepared artificially, either by direct polypeptide synthesis, or, more preferably, by in vivo expression of the corresponding mutant gene in a suitable host cell. This gene may be obtained directly from the genome of the mutant erythrocyte precursor (a mature erythrocyte does not contain DNA), as a complementary DNA (cDNA) transcribed from the messenger RNA of the mutant erythrocyte precursor, by direct polynucleotide synthesis, or, preferably, by in vitro mutagenesis of the gene encoding conventional hemoglobin.

If one of the chains is identical to that of "conventional" hemoglobin, it may be obtained either naturally or synthetically. In addition, to create a functional hemoglobin molecule, it is necessary to provide the prosthetic heme groups and to couple the alpha and beta chains.

It is also within the contemplation of this invention to prepare and use non-naturally occurring low affinity mutants by appropriate modification and expression of the alpha or beta globin gene and subsequent assembly of a recombinant hemoglobin. Methods for selecting candidate sequences and evaluating their suitability for use in a blood substitute product are described herein.

We also have discovered that human alpha-globin may be obtained from a bacterial host by (1) constructing a fused gene which comprises not only the alpha-globin gene but also at least a portion of the beta globin gene, separated by spacer DNA encoding a selective protease cleavage site; (2) expressing the fused gene in the form of a fusion protein; and (3) cleaving the fusion protein at the aforementioned cleavage site in order to liberate the human alpha-globin.

As a result of this discovery, it is possible to prepare entirely artificial human hemoglobin, that is, hemoglobin in which both the alpha and beta globin chains are formed in cells other than human erythrocytes. Such fully artificial hemoglobin is ideal for use in blood substitute solutions. Of course, semi-artificial hemoglobins (one chain obtained from non-erythrocyte source) may still be used.

SUBSTITUTE SHEET

When extracted natural hemoglobin is used as a blood substitute, one must be concerned with the toxicity of red blood cell membrane components which might contaminate the product. It is known that erythrocyte stroma can cause dyspnea, bronchospasm, hypotension, arrhythmia, disseminated intravascular coagulation, activation of complement, and renal, myocardial and hepatic changes associated with ischemia and acute inflammation. See Feola, Surgery, Gynecology & Obstetrics, 166: 211-222 (March 1988); MacDonald, et al., F.A.S.E.B. J., 2(6) Abstr. 8217 (1988); Stone, et al., Surgery, Gynecology and Obstetrics, 149: 874-876 (1979); Rabiner, et al, J. Exp. Med., 126: 1127-42 (1967). While purified preparations of natural hemoglobin are known (so called "stroma-free hemoglobin"), Feola comments, "a truly pure hemoglobin solution has not been produced."

Another concern with natural hemoglobin is contamination with infectious agents communicated by blood. Bove, Progr. Hematol., 14: 123-145 (1986) reported that hepatitis viruses, cytomegalovirus, Epstein-Barr virus, serum parvoviruses, syphilis, malaria, filariasis, trypanosomiasis, babesiosis, numerous pathogenic bacteria, and AIDS are all transmitted by blood transfusions. AIDS has even been transmitted by blood transfusions screened as negative for HIV antibody. Ward, et al., New Engl. J. Med., 318: 473-78 (1988).

The alpha-globin of the present invention may be identical in sequence to natural normal human alpha-globin or to a naturally occurring hemoglobin mutant,

or it may be an alpha-globin mutant which is not known in nature.

5 Mutant hemoglobins, whether of reduced or enhanced oxygen affinity, may be of value for altering O₂ concentrations in cell cultures, or for extracting O₂ from fluids.

10 The appended claims are hereby incorporated by reference into this specification as a statement of the preferred embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

15 Figure 1 shows the amino acid sequence of the (a) alpha and (b) beta chains of conventional human hemoglobin A, and the nucleotide sequences encoding these chains.

20 Figure 2 shows selected DNA sequences and enzyme restriction maps of (a) M13 mp11 FX, (b) pLcIIFX beta, and pLcII beta, and (c) pLcIIFX-beta-FX-alpha. Note that pLcIIFX alpha lacks the codon encoding beta His 2 in Figure 2(b).

25 Figure 3 shows equilibrium oxygen binding curves for artificial conventional human hemoglobin and mutant human hemoglobin having the structure of Hgb Kansas.

30

DETAILED DESCRIPTION OF THE INVENTION

One aspect of this invention is the cloning and expression of an exogenous alpha globin gene in a
35 suitable host. The host may be a procaryotic cell

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(such as a E. coli) or a eucaryotic cell (such as a yeast cell or a mammalian cell). The alpha globin gene will usually code on expression for a polypeptide corresponding to a naturally occurring human alpha globin, normal or abnormal, but may correspond to a nonhuman alpha globin, or indeed be a non-naturally occurring analogue of known alpha globins. Preferably, a mutant alpha globin is prepared and assembled into a low affinity hemoglobin mutant for use in a blood substitute composition.

The alpha globin gene is expressed as part of a fused gene which also codes on expression for at least a portion of the beta globin gene. In a preferred embodiment, the alpha and beta globin sequences are separated by spacer DNA encoding a selective protease cleavage site, in particular, a site susceptible to specific cleavage by Factor Xa.

Preferably, the aforementioned fused gene includes a subsequence which codes on expression for the 20 amino acid N-terminal of beta globin.

As previously noted, the alpha globin of the present invention is advantageously combined with rDNA-derived beta globin and a source of heme to obtain fully artificial (derived entirely from sources other than blood) hemoglobin. Such hemoglobins, and especially low oxygen affinity hemoglobin mutants produced through use of selectively modified alpha and/or beta globin genes, are of value as blood substitutes. Semi-artificial hemoglobins, in which the only chain obtained from a non-erythrocyte source is a mutant sequence and the mutation imparts reduced oxygen affinity to the molecule, are also encompassed by the

SUBSTITUTE SHEET

present invention and may also be used as blood substitutes. Unless otherwise indicated, the term "artificial" embraces both wholly and semi-artificial forms.

5

In order to appreciate possible strategies for designing low affinity alpha or beta mutants of hemoglobin for use as blood substitutes, it is necessary to understand the structure of the hemoglobin molecule.

10

The structure of conventional hemoglobin is well known. We herewith incorporate by reference the entire text of Bunn and Forget, eds., Hemoglobin: Molecular, Genetic and Clinical Aspects (W.B. Saunders Co., Philadelphia, PA: 1986) and of Fermi and Perutz "Hemoglobin and Myoglobin," in Phillips and Richards, Atlas of Molecular Structures in Biology (Clarendon Press: 1981).

15

20

The primary structure of a polypeptide is defined by its amino acid sequence and by identification of any modifications of the side chains of the individual amino acids.

25

About 92% of the normal adult human hemolysate is Hgb A (designated alpha₂ beta₂, because it comprises two alpha and two beta chains). The alpha chain consists of 141 amino acids (See Figure 1). The iron atom of the heme (ferroprotoporphyrin IX) group is bound covalently to the imidazole of his 87 (the "proximal histidine"). The beta chain is 146 residues long (see Figure 1) and heme is bound to it at His 92.

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Other recognized hemoglobin species are Hgb A₂, Hgb A_{1a}, Hgb A_{1b}, and Hgb A_{1c}, as well as the rare species Hgb F, Hgb F₁, Hgb Gower-1, Hgb Gower-2, Hgb Portland, Hgb H, and Hgb Bart. They are distinguished
5 from Hgb A by a different selection of polypeptide chains.

Segments of polypeptide chains may be stabilized by folding into one of two common conformations, the
10 alpha helix and the beta pleated sheet. In its native state, about 75% of the hemoglobin molecule is alpha-helical. Alpha-helical segments are separated by segments wherein the chain is less constrained. It is conventional to identify the alpha-helical segments of
15 the each chain by letters, e.g., the proximal histidine of the alpha chain is F8 (residue 8 of helix F). The non-helical segments are identified by letter pairs, indicating which helical segments they connect. Thus, nonhelical segment BC lies between helix B and
20 helix C. In comparing two variants of a particular hemoglobin chain, it may be enlightening to attempt to align the helical segments when seeking to find structural homologies. For the amino acid sequence and helical residue notation for conventional human
25 hemoglobin A₀ alpha and beta chains, see Table 4.

The tertiary structure of the hemoglobin molecule refers to the steric relationships of amino acid residues that are far apart in the linear sequence,
30 while quaternary structure refers to the way in which the subunits (chains) are packed together. The tertiary and quaternary structure of the hemoglobin molecule have been discerned by X-ray diffraction analysis of hemoglobin crystals, which allows one to

SUBSTITUTE SHEET

calculate the three-dimensional positions of the very atoms of the molecule.

In its unoxygenated ("deoxy", or "T" for "tense") form, the subunits of hemoglobin (alpha1, alpha2, beta1, and beta2) form a tetrahedron having a twofold axis of symmetry. The axis runs down a water-filled "central cavity". The subunits interact with one another by means of Van der Waals forces and hydrogen bonds (and, in the case of deoxyhemoglobin, by "salt bridges"). The alpha1beta1 and alpha2beta2 interfaces remain relatively fixed during oxygenation. In contrast, there is considerable flux at the alpha1beta2 (and alpha2beta1) interface. In its oxygenated ("oxy", or "R" for "relaxed" form), the intersubunit distances are increased.

The deoxy conformation is stabilized by numerous interactions, including, for example, the hydrogen bond between Tyr42alpha and Asp99beta. In the oxygenated form, this bond is broken and a new one formed between Asp94alpha and Asn102beta.

Various different approaches to modification of hemoglobin may be adopted. In each case, a candidate mutant is selected which, on the basis of the available evidence, is believed to be likely to have a lower affinity for oxygen than conventional hemoglobin.

In making this selection, it is possible to consider not only the known effects of various mutations of human hemoglobin, but also the oxygen binding capacity of known forms of animal hemoglobins, and of related compounds such as carboxyhemoglobin, methemoglobin, myoglobin, etc.

Alpha Chain Mutants

Thanks to our success in overcoming the problems of expressing the alpha globin gene in a heterologous system, it is now possible to conveniently prepare alpha globin mutants.

Several low oxygen affinity hemoglobin alpha chain mutants are already known. Of these, Hb Titusville (alpha94Asp=>Asn), Hb Setif (alpha94Asp->Tyr), Hb Torino (alpha43Phe->Val), Hb Hiroasaki (alpha43Phe->Leu) and Hb Moabit (alpha86Leu->Arg) are of special interest.

Alpha globins are more readily oxidized than beta globins because the His(F8) to O₂ bond on the alpha chain is slightly stronger than on beta, so that an electron is more readily lost by the oxygen. Alpha globins could be modified to make them less oxidizable, for example, by the change alpha63His->Gln or Val.

Chloride ion binds to the alpha chain by bridging between the N-terminal NH₃⁺ and the hydroxyl of alpha131Ser. The effect of chloride binding is to increase the P₅₀ slightly. It is believed that by changing alpha131 to Glu, Asp or Asn one could achieve the same effect without resorting to chloride. Alternatively, the pK_a of the N-terminal could be increased. The natural human N-terminal is valine, with a pK_a of 9.72. This could be replaced with Ile (9.76), Pro (10.60) or Thr (10.43).

Beta globin mutants, and additional alpha globin mutants which are likely to impart reduced oxygen affinity, are discussed below.

Stabilizing the T state

It is not possible to raise the plasma
5 concentration of 2,3-DPG sufficiently to maximize the
oxygen carrying efficiency of free conventional
hemoglobin in the blood. This problem can be overcome
by stabilizing the T state with additional salt-bridges
or hydrogen bonds introduced by protein engineering.
10 The cross-linking of hemoglobin may itself stabilize
the T structure to some extent.

Hydrogen bonds and ionic salt bridges are the
predominant stabilizing forces on the surface of
15 proteins. Hydrogen bonds are weak non-ionic bonds
formed between electronegative atoms (eg. oxygen,
nitrogen, sulfur) and protons that are covalently
attached to other electronegative atoms. Individually,
hydrogen bonds are weak (eg -1 kcal/mol), but in a
20 protein there are hundreds to thousands of hydrogen
bonds that collectively amount to a large stabilizing
force. An example of an hydrogen bond that is
important to hemoglobin structure is the hydrogen bond
formed between alpha-asn⁹⁴ and beta-asn¹⁰² in the oxy-
25 state. When either of these residues is mutated to a
residue that can no longer form this hydrogen bond the
oxy state is destabilized and the molecule has a much
lower O₂ affinity. Hg Kansas (beta thr¹⁰²), Hg Beth
Israel (beta ser¹⁰²), Hg Richmond (beta lys¹⁰²), Hg St.
30 Mande (beta tyr¹⁰²), Hg Titusville (alpha asn⁹⁴) and Hg
Setif (alpha tyr¹⁰²) are all examples of the importance
of this hydrogen bond. Other likely non-natural
mutants that will achieve the same effect are beta
asp¹⁰², beta glu¹⁰², beta arg¹⁰², beta his¹⁰², beta

gly¹⁰² and beta cys¹⁰²; alpha gln⁹⁴, alpha thr⁹⁴, alpha ser⁹⁴, alpha lys⁹⁴, alpha gly⁹⁴ and alpha arg⁹⁴.

5 Ionic interactions are salt forms formed between juxtaposed residues of opposite charge. These interactions are of much greater strength mole for mole than hydrogen bonds. An example of attraction of unlike charges would be the interaction between a lys and asp residue; at physiologic pH both of these
10 residues are charged (positive and negative, respectively). Repulsion of two juxtaposed positive charges or two juxtaposed negative charges may also occur; interactions such as these are destabilizing.

15 Stabilization of the deoxy state of Hg by 2,3-DPG is an example of ionic interaction. The 2,3-DPG molecule is highly charged at neutral pH (5 negative charges) and interacts with eight residues in the 2,3-DPG pocket that are positively charged. It is felt
20 that by engineering more positive charge into this binding pocket that 2,3-DPG would bind more tightly to the engineered Hgb than to HgbA. Another example is the alpha₁/beta₂ interface where alpha asp⁹⁴ hydrogen bonds to beta asn¹⁰². Replacing beta asn¹⁰² with a
25 negatively charged group such as asp or glu will interfere with oxy state stabilization by charge repulsion with the like charged alpha asp⁹⁴.

30 Thus, certain amino acid residue changes can facilitate the formation of the desired hydrogen bonds and salt bridges.

The T conformation can also be stabilized by the
35 substitution of cysteine residues for other residues.

Cysteine residues may be cross-linked by disulfide bonds. Examination of the published x-ray data of methemoglobin suggests that the α_1/β_1 interface would be a logical place to put the disulfide.

5 Conveniently, there are two alpha ala residues, G17 and G18 (ala is sterically similar to cys) adjacent to beta G14 cys. Hence, at first glance it is thought that alpha G17 or G18 would be likely spots for cys residues to be added. Further strategy about where to place
10 disulfides can be guided by Thornton, J.M. J. Mol. Biol. 151, 261-287, 1981. Oxidation of cysteines to disulfide (Cystines) bonds can be carried out by treatment with O_2 or catalyzed by thioredoxin (Pigiet, V Am. Biotech. Lab 6, 48-52, 1988).

15 Modifying residues near the oxygen binding site

Heme (haem) is the prosthetic group of hemoglobin, myoglobin, catalase, peroxidase, and cytochrome b. The
20 heme is inserted in a cleft between the E and F helices. The heme iron is linked covalently to the imidazole nitrogen of the "proximal" F8 histidine. The "distal" E11 valine appears to guard the access of oxygen to the heme pocket.

25 Val-E11 and His-E7 are highly conserved residues which are in Van der Waals contact with the oxygen molecule liganded to the heme iron atoms of hemoglobin; by replacing these residues the intrinsic oxygen
30 affinity of hemoglobin can be altered. Val-E11 has been replaced with Ile, Leu, Ala and Met. The oxygen affinity of the Ala-E11beta mutant was higher than that of HbA; that of the Ile-E11beta mutant was lower. X-ray crystallographic study of the latter mutant showed
35 that the delta-methyl group of the Ile side chain must

be pushed to one side if oxygen is to bind to the iron atom.

Another alteration that we have made is beta
5 His63->Phe. This mutant has an extraordinarily low oxygen affinity (See Table 3).

It has therefore been shown that the oxygen
10 affinity of hemoglobin can be altered at will by replacing residues close to the oxygen binding site. By adjusting oxygen affinity in this way the efficiency of oxygen transport can be maximized in the absence of allosteric effectors such as 2,3-DPG.

15 The following residues of human deoxyhemoglobin are, on a nearest atom-to-nearest atom basis, within 4 angstroms of the heme moiety: Alpha B13(D)Met, C7(E)Tyr, CE1(D)Phe, CE3(E)His, CE4(D)Phe, E7(D)His, E10(D)Lys, E11(D)Val, E14(D)Ala, F4(P)Leu, F7(P)Leu,
20 F8(P)His, FG3(P)Leu, FG5(P)Val, G4(P)Asn, G5(P)Phe, G8(D)Leu, H15(P)Val and H19(P)Leu; and Beta B13(D)Leu, C7(E)Phe, CD1(D)Phe, CD3(E)His, CD4(D)Phe, E7(D)His, E10(D)Lys, E11(D)Val, E14(D)Ala, F4(P)Leu, F7(P)Leu, F8(P)His, FG3(P)Leu, FG5(P)Val, G4(P)Asn, G5(P)Phe,
25 G8(D)Leu, H15(P)Val, and H19(P)Leu. See Fermi, et al., J. Mol. Biol., 175: 159-174 (1984). (In the above list, "P" denotes "proximal", "D", "distal", and "E", "edge-on".)

30 These residues are therefore candidates for modification. Consideration should also be given to pairs contacted through bound water molecules. See Ladner, et al., Mol. Biol., 114: 385-414 (1977).

Mutations of beta residues 42 (CD1), 45 (CD4) and 70 (E14) are of particular interest. Other beta residues of interest include 43 (CE1), 46 (CE4), 58 (E7), 61 (E10) and 62 (E11). Alpha residues of interest include 43 (CE1), 46 (CE4), 58 (E7), 61 (E10) and 62 (E11).

In general, mutations around the heme-O₂ binding site that interfere with O₂ binding are also desirable because of their low-affinity O₂ binding nature. Replacing residues that are adjacent to the face of heme that binds O₂ can result in lower affinity. A naturally occurring mutant Hg Bristol (beta⁶⁷ val-->asp) has been described with low affinity. Other mutants that are desirable are the beta ile⁶⁷ described herein, beta asp⁶⁷ and beta glu⁶⁷. Other residues are also in the vicinity of the O₂ binding site. Histidine E7 (beta his⁶³) can be replaced with phe which results in very low O₂ affinity. The other likely residue for mutation is beta phe⁴²; replacement with trp is likely to result in low O₂ affinity. The corresponding residues of the alpha chain may be altered instead of, or in addition to, these preferred mutations of the beta chain.

Replacing residues at the alpha₁-beta₂ contact and the central cavity.

The oxygen affinity and cooperativity of hemoglobin depend on the relative stabilities of the T (low affinity) and R (high affinity) quaternary states. These two states are in equilibrium with each other but one state may be favored by mutations at the alpha₁-beta₂ contact or in the central cavity. There are many naturally occurring mutations at these sites, and

careful study of these should be of value in designing a hemoglobin molecule with the desired properties.

Thus alpha 1 residues 37(C2)Pro, 38(C3)Thr,
5 40(C5)Lys, 41(C6)Thr, 42(C7)Tyr, 44(CD2)Pro, 88(F9)Ala,
91(FG3)Leu, 92(FG4)Arg, 94(G1)Asp, 95(G2)Pro,
96(G3)Val, 97(G4)Asn, 140(HC2)Tyr, and 141(HC3)Arg are
all known to lie within 4 angstroms of at least one
residue of the beta2 chain of human deoxyhemoglobin.
10 Similarly, beta2 residues 146(HC3)His, 145(HC2)Tyr,
105(G7)Leu, 102(G4)Asn, 101(G3)Glu, 100(G2)Pro,
99(G1)Asp, 98(FG5)Val, 97(FG4)His, 43(CD2)Glu,
41(C7)Phe, 40(C6)Arg, 37(C3)Trp, 36(C2)Pro, 35(C1)Tyr,
and 34(B16)Val lie on the other side of the alphabeta2
15 interface of human deoxyhemoglobin.

Mutation of beta102(G4)Asn is particularly
preferred. Hg Kansas is a known low affinity mutant in
which this residue is altered to Thr. As previously
20 mentioned, the oxy state is stabilized by a hydrogen
bond between beta Asn102 and alpha Asp94. The
preferred mutation would disrupt this hydrogen bond.

Another favored mutation at this site is to beta
25 Asp102. The negative charge-negative charge repulsion
between this group and the alpha Asp94 would further
destabilize the oxy state.

Still other preferred mutations at the beta102
30 locus would be to Ser (Hb Beth Israel), Lys (Hb
Richmond) and Tyr (Hb St. Mande).

Increasing the stability of hemoglobin

35

Inside the erythrocyte the cytochrome b_5 and glutathione reduction systems serve to maintain hemoglobin in the active ferrous form. Free hemoglobin in the bloodstream would rapidly be at least partially oxidized to the ferric state since there is no such means of keeping it in the reduced form outside the red cell. It is possible to stabilize the ferrous form by replacing the Val-E11 residue with a large aliphatic amino acid such as Ile or Leu. A large side chain at this position prevents electron donors from reaching the iron atom and so slows the rate of autoxidation. The His63->Phe mutant is also of interest.

If hemoglobin is cross-linked both intermolecularly to form higher molecular weight aggregates and intramolecularly to prevent dissociation into dimers then it will neither react with haptoglobin nor pass through the glomerular membrane of the kidney. If the oxygen binding properties of haemoglobin are to be unaffected it is important that the cross-linking does not prevent conformational change of the protein. This is because the heme-heme interaction arises from a reversible transition between two quaternary structures: the T structure with low oxygen affinity. These two structures with high oxygen affinity. These two structures differ in the contact between the α_1 and β_2 subunits. Therefore this contact should be allowed to undergo the conformational changes accompanying oxygen association and dissociation.

Site-directed mutagenesis can be used to replace certain surface residues of haemoglobin with cysteinyl residues. Protein engineering techniques similar to those used to introduce new disulfide bridges to

SUBSTITUTE SHEET

lysozyme, subtilisin and dihydrofolate reductase can be used. Hemoglobin molecules carrying such -SH groups can be cross-linked by disulfide bridges or via a bifunctional thiol reagent. It should also be noted
5 that there is a natural mutant (Hb Ranier) in which His 143 beta is replaced by Cys and the newly introduced cysteine forms a disulfide bridge with Cys 93 beta *in vivo*. This mutant is more stable than native Hb.

10 Table 2 is a list of candidate, non-naturally occurring hemoglobins which are expected to exhibit a lower affinity for oxygen than does conventional hemoglobin.

15 After determining the amino acid sequence changes which distinguish the desired hemoglobin from conventional hemoglobin, it is necessary to design the expression vector. The most convenient starting point is a nucleotide sequence which codes upon expression
20 for conventional hemoglobin. This sequence then may be modified by site-specific mutagenesis.

Techniques of site-specific mutagenesis are well known, and this invention is not limited to any
25 particular technique. The two principal techniques are the gapped duplex A.A., Kruse, K. B., Brown, J.L. BioTechniques 6, 338-339, 1988) and M-13 (Zoller, M.J. and Smith, M. Meth. Enz. 100, 468-500, 1987) methods.

30 Alternatively, a subsequence with the desired mutation may be synthesized and then ligated to other subsequences to form the desired molecule.

The gene must be placed under the control of a
35 promoter. Either a constitutive or an inducible

promoter may be used; the advantages and disadvantages of each are well known in the molecular biology art. A promoter must be chosen which is functional in the host. Thus, a bacterial promoter would be chosen if the expression vector is to be introduced into a bacterial host, a yeast promoter, if a yeast host, and a mammalian promoter, if a mammalian cell host. It should be understood that the promoter of a viral gene of a virus which infects the chosen host cell may also be used. The present invention does not depend upon the choice of either the promoter or the host. However, it is desirable to choose a host so that the subsequent purification of the mutant hemoglobin is not unduly complicated.

For the same reason, it is preferable, but not required, that the mutant hemoglobin be expressed as a moiety of a fusion protein. Attempts to express the alpha chain other than as a fusion protein were largely unsuccessful. However, the entire alpha chain sequence could be expressed as part of a fusion protein including a portion of the beta chain, and separated from the latter by a spacer providing a selective cleavage site. The hemoglobin is obtained merely by placing the secreted fusion protein in an appropriate cleavage environment. Numerous fusion protein/cleavage system combinations are now known in the art.

After expressing, recovering and purifying the mutant hemoglobin, its P_{50} is measured in accordance with the protocol set forth in the Reference Example. Preferably, its P_{50} is at least 10% higher than that of conventional hemoglobin A when measured in the same environment.

While it is not practical to combine stroma-free conventional hemoglobin with sufficient 2,3-DPG to restore its P_{50} to intra-erythrocyte levels, it may be possible to combine a modestly right-shifted mutant hemoglobin with a small amount of 2,3-DPG or functionally similar organic phosphate (e.g., pyridoxal phosphate or ATP-dialdehyde) so as to mimic the oxygen-carrying capacity of whole blood. The half life of the organic phosphate may be improved by encapsulating the organic phosphate and the mutant hemoglobin in a liposome to obtain a "simulated erythrocyte," or by covalently attaching the organic phosphate group to the hemoglobin.

15 Reference Example

Our preferred method of measuring the P_{50} of purified hemoglobin solutions for the purpose of the appended claims is as follows.

Hemoglobin-oxygen equilibrium data are measured using a thin film technique (Imai, K. Meth. Enz. 76, 438-449, 1981). A sample of hemoglobin (0.6 mM) in buffer (50 mM Bis-Tris or 100mM HEPES), pH 7.4, 0.1M NaCl, is applied to the cell and then equilibrated at 25°C. The hemoglobin is saturated with O_2 by a stream of air, or air/ O_2 if the hemoglobin has low O_2 affinity or if the local barometric pressure prevents ambient oxygen from achieving a high enough partial pressure to saturate the molecule. Deoxygenation is achieved by closing the cell to O_2 flow and flushing the cell with N_2 (>99.98% pure). The oxygen equilibrium curve is obtained by plotting the change in absorbance at 560 nm against the pressure of O_2 in the cell. Percent saturation is determined by measuring the A^{560} at a

given partial pressure (i) divided by the A^{560} of the beginning, totally saturated Hgb solution Hgb solution $[A^{560} (i)/A^{560} (100\%) \times 100 = \% \text{ saturation}]$. The P_{50} is defined as the partial pressure (i) of O_2 required to cause 50% saturation of O_2 binding sites.

P_{50} may also be measured under other conditions, but it should be noted that many environmental factors affect hemoglobin's oxygen affinity. The effect of Ph, CO_2 , inorganic anions, organic phosphates and temperature on P_{50} are discussed in Bunn and Forget, HEMOGLOBIN:MOLECULAR, GENETIC AND CLINICAL ASPECTS 37-47, 95-98 (W.B. Saunders Co.: 1986).

Since many determinations of whole blood oxygen binding curves are made under standard physiologic conditions ($37^\circ C$, $pH=7.4$, $PCO_2=40 \text{ mm Hg}$), it may be necessary to adjust literature figures. In this context, it should be noted that a $10^\circ C$ increase results in nearly a two-fold increase in P_{50} , while the dependence of P_{50} on pH is approximately given as $\Delta \log P_{50}/\Delta pH = -0.5$.

Comparing P_{50} values of purified Hb preparation to P_{50} values of whole blood can be problematic. Whole blood, or isolated RBC's, contain many components that naturally modulate the shape of the hemoglobin-oxygen binding curve. The RBC encapsulates Hgb in the presence of a high concentration of the effector molecule 2,3-DPG; a molecule that causes Hgb to have a markedly lower affinity for O_2 . Other intra-erythrocyte components also affect the shape of the binding curve: ATP, Cl^- , CO_2 , H^+ , orthophosphate, methemoglobin and carboxyhemoglobin. These substances are not normally present in purified Hgb solutions and

thus, the P_{50} value of purified Hgb is lower than that found in whole blood. One very important modulator of Hgb-oxygen affinity is Cl^- ion. Cl^- ion is found outside the erythrocyte in the blood serum at a physiologic concentration of approximately 0.15M. Since Cl^- causes a lower O_2 affinity, a Hgb solution with a P_{50} measured in vitro may well have much lower O_2 affinity if infused into the blood stream. Another problem with measuring O_2 binding of whole blood is that RBCs are quite fragile and in the process of manipulating the erythrocyte into the instrument used to measure the O_2 binding it is inevitable that at least a small percentage of the RBCs will lyse. Lysed RBCs leak Hgb into the surrounding media away from 2,3-DPG; hence, since free Hgb has a higher affinity than intraerythrocyte Hgb, lysed RBCs will have a higher O_2 affinity and can cause a falsely low P_{50} value for whole blood P_{50} determinations. It is widely accepted that under physiologic conditions whole blood has a P_{50} value of 26-28 mmHg. When Hgb is isolated from whole blood, however, the measured P_{50} is on the order of 1-10 mmHg depending on the investigators experimental conditions. For these reasons it is most accurate to measure Hgb-oxygen equilibria with purified Hgb molecules under strict conditions of buffer, pH and salt concentration. Unfortunately, there are no accepted "standards" for all investigators to measure Hgb oxygen binding in in vitro systems.

Still, as many mutant hemoglobins are first identified in patient's whole blood, one would like to be able to compare the relative affinities of native and mutant Hgb for O_2 , between whole blood and purified Hgb preparations. An example of this is Hgb Chico (beta lys⁶⁶-->thr) (Table 1). If one examined only the

P₅₀ value of the purified mutant Hgb (10.1 mmHg) one would note that Hgb has a P₅₀ value less than that for normal whole blood (27.2 mmHg). Still, when that hemoglobin is measured in RBCs under physiologic conditions it is apparent that it does have a higher P₅₀ than normal whole blood (38 mmHg). One cannot predict the degree that the P₅₀ value will change going from whole blood Chico to a purified Hgb Chico if it were infused into the bloodstream as a blood substitute. One can conclude, however, that the P₅₀ will be higher than it is in pure form, and that by reacting the mutant Hgb with organic phosphates that P₅₀ will be even higher.

Note also that whole blood oxygen binding curves are customarily determined under standard physiologic conditions (37°C, pH 7.4, PCO₂=40 mmHg) and red cell 2,3-PDG varies with age, sex and condition.

(Example 1: Production of Artificial Conventional Hemoglobins)

Construction of M13 mp11 FX

M13 mp11 FX encodes a sequence (Ile-Glu-Gly-Arg) including the recognition site for factor X_a. This M13 derivative can be used to join any coding sequence to the factor X_a recognition sequence. See Nagai, EP Appl 161,937 (CELLTECH LTD.) However, this invention is not limited to the use of either M13 or of the factor Xa cleavage system.

All DNA manipulations were carried out essentially as described by Maniatis et al ('Molecular Cloning' Cold Spring Harbour, New York, 1982). A temperature-sensitive lysogenic strain MZ-1 (galK_{am} 8attL

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BamN₇N₅₃CI857 H1, his⁻, ilv⁻, bio⁻, N⁺, a gift from Dr. K. McKenney and available on request from Medical Research Council) was used as a host strain for plasmids containing lambda P_L promoter and transformation was carried out by the method of Remaut et al (Gene 15, 81-93 (1981)). Other promoters and host strains could have been employed.

T4 DNA ligase was prepared from strain NM989 (Murray et al, J Molec Biol 132, 493-505 (1979) and Tait et al, J Biol Chem 255, 813-815 (1980)). Restriction enzymes were purchased from New England BioLabs.

Two oligonucleotides dTACCCTCGATGGATC and dCATCGAGGGTAGGCC were synthesized by a phosphotriester method on a controlled pore glass support (Sproat et al, Tetrahedron Lett, 24, 5771-5774 (1983)) and purified by HPLC (Gait et al, Nucleic Acids Research 10, 6243-6254 (1982)). These oligonucleotides encode the peptide sequence (gly)-ser-ile-glu-gly-arg in a BamHI-StuI linker. The two oligonucleotides were allowed to anneal after phosphorylation with T4 polynucleotide kinase (P-L, Biochemicals) and r[gamma-³²P]ATP (3000 Ci/m mol, Amersham) and ligated to form concatamers. The DNA was then digested with Bam HI and cloned into the dephosphorylated Bam HI site of M13 mp11 (Vieira et al, Gene 19, 259-268 (1982)) to yield M13 mp11 FX, as shown in Figure 1a, which forms blue plaques in the presence of isopropyl-beta-D-thiogalacto-pyranoside and 5-bromo-4-chloro-3-indolyl-beta-d-galactoside (Sigma).

Construction of mp11 FX alpha-globin

40 micro g of cloned human alpha-globin cDNA were digested with the restriction enzymes Nco I and Apa I. The single-stranded ends of the excised alpha-globin fragment were trimmed by incubation at 0°C for 10 minutes with 200 units of mung bean nuclease (P-L Biochemicals) in 30 mM sodium acetate pH 4.6, 50 mM sodium chloride, 1 mM zinc chloride, 5% glycerol. The alpha-globin sequence was then cloned into the Stu I site of M13 mp11 FX described above (Nagai & Thogersen, Nature 309, 810-812). The DNA sequences of several clones were determined (Sanger et al Proc. Natl. Acad. Sci. USA, 74, 5463-5467 (1977)) and a clone in which the first valine codon of the alpha-globin gene was joined to the DNA sequence encoding the factor X_a recognition site (Ile-Glu-Gly-Arg) was named mp11 FX alpha-globin.

Construction of pLcII beta and pLcIIFX beta

Plasmids pLcIIFX beta and pLcII beta direct efficient production of a hybrid protein consisting of the 31 amino-terminal residues of the lambda CII protein and the complete human beta-globin, with and without the factor X_a cleavage site, respectively.

The Eco-Hind III fragment containing the multi-restriction sites was cut out from M13 mp10 (Vieira et al, supra) and ligated to Eco RI-Hind III cut pLc245 (Remaut et al, supra) to form pLmp10. The 319 bp Alu I fragment containing the nutR, t_{p1} sites and a part of the cII gene was cut out from pKG1805 (McKenney, K PhD Dissertation, The Johns Hopkins University (1982)) and cloned into the Sma I site of M13 mp10 in the same orientation with respect to the beta-galactosidase alpha-peptide gene. The Eco RI-Hind III fragment

SUBSTITUTE SHEET

containing the lambda DNA sequence was then cut out and cloned into the Eco RI-Hind III site of pLmp10 to yield pLcII.

5 A complete human beta-globin cDNA sequence was reconstructed by joining restriction fragments prepared from an incomplete cDNA clone (pJW102) (Wilson et al, Nucleic Acids Research 5, 563-581 (1978)) and a genomic DNA clone (Lawson et al, Cell 21, 647-651 (1980)) and
10 cloned into the Sma I-Hind III site in M13 mp9. M13 mp9 beta cDNA thus obtained was opened at the Nco I site which is located at the initiation codon and treated with Klenow DNA polymerase (Boehringer Mannheim) in the presence of 100 micro M 4dNTP to
15 obtain flush ends. The beta-globin cDNA sequence was then cut out with Hind III and inserted into the Bam HI (filled-in)-Hind III site of pLcII so that the beta-globin gene was fused to the lambda cII gene in phase via a small linker DNA derived from M13 mp10.

20 In order to construct pLcIIFX beta, M13 mp9 beta cDNA was opened with Nco I and 40 micro g of DNA was treated with 200 units of mung bean nuclease (P-L Biochemicals) in 30 mM Na-acetate pH 4.6, 50 mM NaCl, 1
25 mM ZnCl₂, 5% glycerol at 0°C for 10 min to remove the 5' protruding end. The beta-globin cDNA sequence was cut out with Hind III and cloned into the Stu I-Hind III cut M13 mp11 FX. The DNA sequence was determined by the dideoxy chain termination method (Sanger et al,
30 PNAS 74, 5463-5467 (1977)) to ensure that the first valine codon of the beta-globin gene was preceded by the DNA sequence coding for Ile-Glu-Gly-Arg. Then, the Bam HI fragment containing a part of the beta-globin sequence was cut and cloned into Bam HI digested pLcII
35 beta to form pLcIIFX beta, as shown in Figure 1b.

SUBSTITUTE SHEET

Construction of pLcII FX beta FX alpha

M13 mp11 FX beta-globin DNA was prepared in single-stranded form and a BglII site was introduced into the beta-globin sequence using a mutagenic oligodeoxynucleotide, dACCAACTTCAGATCTGTTACCTTG, called KN83, to obtain mp11 cII FX beta FX. The replicative form of this mutant clone was digested with SacI and Hind III, and the resulting cII FX beta FX fragment was cloned into Sac I/Hind III cut pLmpII to form pLcII FX beta FX. This recombinant plasmid was digested with BglII and the 5' terminal phosphate groups of the linear DNA were removed with calf intestinal alkaline phosphatase. The replicative form of mp11 FX alpha-globin was digested with BamHI and the FX alpha-globin containing fragment was ligated with the linearised pLcII FX beta FX to form pLcII FX beta FX alpha. This plasmid encodes a fusion protein consisting of the 31 amino-terminal residues of the lambda phage cII protein, the tetrapeptide Ile-Glu-Gly-Arg, the 20 amino-terminal residues of human beta-globin, the tetrapeptide Ile-Glu-Gly-Arg and human alpha-globin at the carboxyl end. Transcription of the fusion protein gene is initiated at the lambda P_L promoter and is regulated by lambda repressor.

Expression of Recombinant Conventional Alpha and Beta Globin

A defective lambda phage lysogenic strain of E.coli QY13 (a gift from S. Brenner, and available on request from Medical Research Council) harboring pLcIIFX beta FX alpha-globin or pLcIIFX beta-globin was grown at 30°C in 2xTY medium (16g tryptone, 10g yeast extract and 5g sodium chloride-litre) in the presence of ampicillin (25 micro g/ml). When the optical

density (600 nm) reached 1.5-1.6, the temperature was quickly raised and maintained at 42°C for 15 min, followed by further incubation at 37°C for 3-4 hr. The cells were harvested and frozen in liquid nitrogen.

5

The cells (100g) were thawed and suspended in 80 ml of 50 mM Tris-HCl (pH 8.0)/25% sucrose (wt/vol)/1 mM EDTA and lysed by addition of lysozyme (200 mg). Then, MgCl₂, MnCl₂ and DNase I were added to final
10 concentration of 10 mM, 1mM and 10 micro g/ml, respectively. After 30 min incubation 200 ml of 0.2 M NaCl/1% deoxycholic acid/1.6 % Nonidet P-40 (vol/vol)/20 mM Tris-HCl(pH7.5)/2 mM EDTA were added to the lysate, which was then centrifuged at 5000 x g for
15 10 min. Then the pellet was suspended in 0.5 % Triton X-100/1 mM EDTA and centrifuged. This procedure was repeated until a tight pellet was obtained. The protein pellet was finally dissolved in 8 M urea/ 25 mM Tris-HOAc (pH5.0)/1 mM EDTA/1 mM dithiothreitol in the
20 case of cIIFX beta-globin fusion protein. In the case of cIIFX beta-FX-alpha-globin fusion protein, the pellet was first dissolved in 6M guanidine hydrochloride/25 mM Tris-HOAc (pH 5.0)/1 mM EDTA/1 mM dithiothreitol.

25

The fusion protein solution was then applied to a 4 x 10 cm CM-Sepharose (Pharmacia) column equilibrated with the same buffer. The fusion protein was eluted with a linear gradient formed with 500 ml of 8 M
30 urea/25 mM Tris-HOAc pH 5.0/1 mM EDTA/1mM dithiothreitol and 500 ml of the same buffer with 0.2 M NaCl. The fusion protein was further purified on a 5 X 60 cm Sephacryl S-200 column equilibrated with 5 M guanidine-HCl/50 mM Tris-HCl/1 mM EDTA/1 mM
35 dithiothreitol to remove any trace of impurities. The

combined fraction was extensively dialyzed against 50 mM Tris-HCl (pH 8.0)/0.5 M urea/1mM CaCl₂.

Protein Cleavage

5

The cIIFX beta FX alpha-globin or cIIFX beta-globin fusion protein was incubated at 0°C with blood coagulation factor X_a that had been activated with Russell's viper venom immobilized on cyanogen bromide-activated Sepharose-6B. 100 micro l aliquots were removed after intervals of 2, 5, 15, 30, 60 and 120 minutes. 100 ul of protein sample buffer (Laemmli, 1970) and 1 ul of 100 mM DTT were added to each aliquot, which was then boiled before being applied to an SDS polyacrylamide gel. Factor X_a cutting of the cIIFX beta FX alpha fusion protein gives rise to a number of polypeptide products. This is due to the presence of two recognition sites within the protein. Complete digestion releases three polypeptides, a cII protein fragment and a beta-globin fragment, both with the tetrapeptide Ile-Glu-Gly-Arg at the carboxyl terminus, and the desired alpha-globin. Partial digestion of the fusion protein gives two other products.

25

Factor X_a cleavage of cIIFX-beta yields two products, a cII fragment and the desired beta globin.

Formation of Semi-Artificial Hb with alpha-globin produced in E.coli

30

25 mg of hemin-Cl was dissolved in 2.5 ml of 0.1 N KOH and 30 diluted with 20 ml of water and 2.5 ml of 1 M KCN. The native beta chain was diluted in 20 mM K phosphate buffer pH 5.7, 1 mM EDTA, 1mM dithiothreitol

35

(DTT) and bubbled with CO. Alpha globin produced in E.coli was dissolved in 8 M urea/50 mM Tris-Cl pH 8/1 mM EDTA/1 mM DTT at the concentration of 5 mg/ml and incubated at room temperature for 3 hours. The alpha-globin solution was added dropwise to 20 volumes of 30 mM K phosphate buffer pH 5.7, 1 mM EDTA, 1 mM DTT with gentle stirring. The hemin-dicyanide solution (1.2 equivalent to the alpha-globin) was added dropwise to the alpha-globin solution and the beta chain was added in slight excess. The semi-artificial Hb was dialyzed overnight against 0.1 M K phosphate pH 7.6 1 mM EDTA, 1 mM KCN.

Formation of semi-artificial Hb with beta-globin produced in E.coli

Beta-globin (100 mg) was dissolved in 8 M urea, 50 mM Tris-Cl pH 8.0, 1 mM DTT, 1 mM EDTA at the concentration of 5 mg/ml and incubated at room temperature for 1 hr. The beta-globin solution was added dropwise to 16 volumes of alpha chain solution (either isolated from Hgb A, or produced by recombinant means) (3.2 mg/ml) in 10 mM Tris-Cl pH 8.0. The hemin-dicyanide solution (1.2 equivalents to beta-globin) was added dropwise with gentle stirring. The semi-artificial Hb was dialyzed against 2 changes of 0.1 M K phosphate pH 7.4 1 mM EDTA, 1 mM KCN.

Formation of wholly artificial hemoglobin

The lyophilized recombinant alpha and beta globins were dissolved in 8M urea/50 mM Tris-Cl, pH 8.0/1 mM EDTA/1 mM DTET, diluted to a concentration of 5 mg/ml and incubated at room temperature for 3-4 hours. The alpha globin was then diluted to 0.3 gm/ml with chilled

20 mM K_2HPO_4 , pH 5.7/1 mM EDTA/1 mM DTT. Hemin (25 mg) was dissolved in 2.4 mg 0.1 M KOH, diluted with an equal volume of 1 M KCN; this solution was then made 0.1 mg/ml in hemin and 20 mM K_2HPO_4 , pH 6.7 with stock phosphate buffer. Hemin from this solution was added to a 2.8 molar excess to chilled alpha-globin; and equal molar amount of beta-globin was added and the solution was dialyzed at 4°C overnight against 0.1 M K_2HPO_4 , pH 7.6/1 mM EDTA/1 mM KCN.

Purification of the semi-artificial or wholly artificial Hb

The artificial Hb was concentrated by ultra-filtration using diaflo PM-10 membrane (Amicon) and transferred into a 200 ml screw-top test tube with a rubber septum. The hemoglobin solution was deoxygenated by evacuation and flushing with N_2 , and then the solution was saturated with CO. 100 mM Sodium dithionite solution was prepared anaerobically in a 20 ml screw-top test tube with rubber septum. 4.5 equivalents of dithionite were added to the Hb solution with a syringe, and the mixture incubated on ice for 15 min.

The Hb solution was gel-filtered against 10 mM Na phosphate buffer pH 6.0 on a 4 X 40 cm Sephadex G-25 (fine) column. The Hb was then applied to a 2 X 10 cm CM-52 (Whatman) column equilibrated with the same buffer and the chromatography was developed with a linear gradient of 500 ml 10 mM Na phosphate buffer pH 6.0 and 500 ml of 70 mM sodium phosphate buffer pH 6.9. CO was removed from Hb by photolysis under a stream of oxygen. This Hb shows native oxygen binding properties.

A wholly artificial hemoglobin may be prepared by the combination of alpha-globin and beta-globin both produced in E.coli, or any other host of a non-erythroid nature, with a source of heme.

Example 2: Production of Low-Affinity Hemoglobin Mutants

10 Construction and Mutagenesis of pLcIIFXbeta-globin(Thr¹⁰²)

A synthetic oligonucleotide of sequence dGGAGCCTGAAAGTCTCAGGA was designed from published mRNA sequence information [Bunn & Forget, eds., Hemoglobin: Molecular, Genetic and Clinical Aspects, W.B. Saunders Co., Philadelphia, PA, 169-222 (1986)] and synthesized on a controlled glass support. The oligonucleotide was gel purified [Lloyd et al., BioTechniques 4, 8-10 (1986)] and used to prime the site-specific mutagenesis of M13 mp10 cIIFXbeta -globin by the methods of Zoller and Smith [Methods in Enzymology 100, Academic Press, New York, 468-500 (1983)].

The mutagenic oligonucleotide was complementary to the beta-chain structural gene sequence flanking and centered upon the wild-type codon for Asn¹⁰². At this triplet specific base substitutions were designed into the oligonucleotide to specify ACT-Thr¹⁰², the amino acid sequence alteration which is characteristic of the Kansas beta-globin mutant [Bonaventura & Riggs, J. Biol. Chem. 243, 980-991 (1968)]. The particular Thr codon employed in this substitution, while differing from that found in the original Kansas isolate (Bonaventura and Riggs, supra), is preferentially

utilized in highly expressed E. coli genes [Grantham et al., Nucleic Acids Res. 9, r43-r74 (1981)].

Production of Mutant beta-Globin

5 The products of the in vitro mutagenesis reaction were transformed into competent E. coli MZ-1 [galK_{am} 8attL BAmN₇N₅₃CI857 H1, his⁻, ilv⁻, bio⁻ N⁺, a gift of Dr. K McKenney and available on request from the Medical Research Council], by standard procedures of
10 CaCl₂-shock [Maniatis et al., Molecular Cloning, Cold Spring Harbor Laboratory, New York, 250-251 (1982); Nagai & Thogersen, Methods in Enzymology, supra].

15 Transformants harboring the desired mutant M13 bacteriophage constructs were then identified by differential plaque-hybridization screenings at high stringency using gamma-[³²P]-end-labeled oligonucleotides as probes.

20 The reactants used to prepare each of the phosphorylated hybridization probes were 300 pM (2 ug) of oligonucleotide, 100 pM (0.7 mCi) gamma-[³²P]-ATP (specific activity approximately 6000 Ci/mM), and 15 units T4 polynucleotide kinase in a total reaction
25 mixture of 50 ul. After 37° C incubation for 2 h, the end-labeled oligomers were purified away from orthophosphate and unincorporated precursor nucleotide using reverse phase C-18 sep-paks (Waters Associates Milford, MA). This latter procedure involved loading
30 the phosphorylation reaction mixture onto the C-18 cartridge in an aqueous salt solution, eluting orthophosphate and unincorporated ATP with water followed by 10% methanol, and then eluting the purified oligomer with 60% methanol. The probes employed
35 comparatively in the differential hybridization

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analyses were both the mutagenic oligonucleotide and another 20-mer (dGGAGCCTGAAGTTCTCAGGA) which is perfectly complementary to the wild-type beta-chain DNA sequence in the same coding region.

5

After identification and plaque purification (Zoller & Smith, supra) of several of the desired M13 phage constructs, one of the resultant Thr¹⁰² mutants, termed M13 mp10 cIIFX beta-globin (Thr¹⁰²), was further
10 verified by DNA sequence analysis [Sanger et al., Proc. Natl. Acad. Sci. USA 74, 5463-5467 (1977)] to contain the desired mutation at codon-102, and only that particular amino acid sequence alteration in the beta-chain structural gene coding sequence.

15

A large scale preparation of M13 mp10 cIIFX-globin(Thr¹⁰²) RF DNA was conducted as follows [Recinos, Ph.D. Dissertation, Vanderbilt University (1987)]. The host E. coli was grown at 37° C overnight
20 in M9 minimal medium (Maniatis et al., supra) plus 2 ug/ml thiamine. 0.3 ml of this cell culture was then diluted (1:50) into 14.7 ml 2X YT medium and growth at 37° C was continued for an additional 2 h. The latter culture was again diluted (1:10) into a final volume of
25 150 ml 2X YT, and this cell solution was inoculated with the plaque purified mutant M13 phage construct at a multiplicity of infection of approximately one. This phage infection was then shaken vigorously at 37° C for 14 h, and cells for RF preparation were harvested by
30 centrifugation (5000 X g, 10 min, 4° C). The mutant phage supernatant was stored at -20° C for use in scaled-up versions of the protocols (Zoller & Smith, supra) for phage purification and for single-stranded template preparation.

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Double-stranded RF DNA was purified from the cell pellets as follows. Pellets were frozen in an alcohol dry-ice bath for 10 min, thawed at 20° C and completely resuspended on ice in 10 ml 25% sucrose, 50 mM Tris-HCl (pH 8.0). Lysozyme was added to a final concentration of 4 mg/ml, and incubation was continued on ice for 5 min. EDTA was then added to a final concentration of 80 mM, and again after 5 min on ice, an equal volume of 0.5% Triton X-100, 50 mM Tris-HCl (pH 8.0), 62.5 mM EDTA was added. This solution was kept on ice for 15 min more, and then 5 M NaCl was added to a final concentration of 1 M. The last solution was loaded into Beckman Type 70 Ti rotor bottles, and after a further incubation on ice for 3 h, was centrifuged at 40,000 rpm for 75 min at 15° C. RF DNA was decanted with the supernatant and precipitated at -20° C for 20 min with the addition of an equal volume of isopropanol. DNA precipitates were pelleted and resuspended in 10 mM Tris-HCl (pH 8.0), 1 mM EDTA, 100mM NaCl, and treated with RNase (final conc. 100 ug/ml) for 2 h at 37° C. This solution was phenol and chloroform extracted (one time each), and the DNA was ethanol precipitated and resuspended in 30 ml 10 mM Tris-HCl (pH 8.0), 1 mM EDTA. The DNAs were twice banded by CsCl-ethidium bromide density gradient equilibrium centrifugation. Form I DNA bands were extracted 4X with CsCl-saturated isopropanol to remove ethidium bromide, and DNA and CsCl were ethanol precipitated. CsCl was removed from DNA pellets by resuspension in and dialysis against 10 mM Tris-HCl (pH 8.0), 0.2 mM EDTA. A final ethanol precipitation and resuspension in 0.5 ml Tris-HCl (pH 8.0) yielded 150 ug of purified M13 mp10 cIIIFXbeta-globin(Thr¹⁰²) RF DNA for use in subcloning the mutant beta-globin

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structural gene into the beta-globin expression construct.

The mutated beta-chain sequence was moved into
5 the beta-chain expression vector, pLcIIFXbeta-globin
(nic⁻), by the following procedures. Mutant clone RF
(50 ug) was restriction enzyme digested with Sac I and
Hind III, and the resultant cIIFX -globin (Thr-102)
10 fragment was isolated from a 1% preparative agarose gel
(Maniatis et al., supra) and gel-purified by a phenol
freeze-thaw procedure [Benson, BioTechniques 2, 77-78
(1984)]. Approximately 200 ug of expression vector DNA
was isolated and purified from E. coli QY13
15 transformant cell pellets by methods nearly identical
to those described above for the Rf preparation. This
plasmid DNA (20 ug) was similarly restricted with Sac I
and Hind III and further treated with bacterial
alkaline phosphatase (Bethesda Research Laboratories,
Gaithersburg, MD, as directed) to remove the 5'
20 phosphates from the vector DNA, thereby preventing
recircularization without insert DNA in subsequent
ligation reactions.

The purified mutant insert DNA fragment was then
25 ligated back into the expression construct at moderate
insert end-concentration, replacing the wild-type
protein coding sequences previously therein. Ligation
reaction conditions (modified from procedure of New
England Biolabs, Inc., Beverly, MA) were: 11 ug vector
30 DNA and 2.1 ug purified insert DNA in 500 mM Tris-HCl
(pH 7.8), 100 mM MgCl₂, 6 mM ATP, 2 mM dithiothreitol;
total reaction volume = 125 ul. Incubation for the
ligation was at 16^o C for 10 h. The final ligation
reaction mixture was used to transform competent E.
35 coli QY13 with selection for ampicillin resistance.

Transformants harboring the desired plasmid construct for the expression of mutant beta-chain were identified by differential colony hybridization screenings [Grunstein & Hogness, Proc. Natl. Acad. Sci. USA 72, 3961-3965 (1975), with modifications] using the end-labeled mutagenic and wild-type oligonucleotides described above as probes. The correct plasmid construct was further verified by restriction analysis and by its expression of a protein which is chromatographed differentially from the wild-type cIIFX beta-globin fusion product by HPLC. The mutant beta-globin was produced, purified and combined with alpha-globin as described for native beta-globin.

15 Construction and Mutagenesis of pLcIIFXbeta-globin(Ile⁶⁷)

Mutation of the val⁶⁷ codon was introduced into the beta-globin cDNA sequence in M13 mp10 cIIFXbeta-globin using the mutagenic primer (dGCACCGAGGATTTTCTTGCC) as above. The mutant beta-globin was produced, purified and combined with alpha globin as described for native beta-globin to obtain a mutant hemoglobin.

25 Construction and Mutagenesis of pLcIIFXbeta-globin(phe⁶³)

Mutation of the his⁶³ codon was introduced into the beta-globin cDNA sequence in M13 mp10 cIIFXbeta-globin using the mutagenic primer (dTCTTGCCGAAAGCCTTCA) as above. The mutant beta-globin was produced, purified and combined with alpha globin as described for native beta-globin to obtain a mutant hemoglobin.

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Characterization of Mutant Hemoglobin

Oxygen equilibrium studies for Hgb (beta phe⁶³)
5 Hgb (beta ile⁶⁷) were performed in 0.05 M bis-Tris pH
7.4, 0.1 M NaCl, at 25°C using the automated recording
apparatus of K. Imai (Meth. Enz. 76, 438-449, 1981) and
for Hgb (beta thr¹⁰²) in 0.1 M HEPES pH 7.4, 0.1 M NaCl
10 76, 427-438, 1981). Results are shown in Table 3.

Example 3: Blood Substitute Solution

The purified hemoglobin is incorporated into a
15 physiologically acceptable blood substitute solution.
A preferred solution includes the following components:

	Hgb (gm/l)	60-120
	Sodium (mEq/l)	135-145
20	Potassium (mEq/l)	3.5- 4.5
	Chloride (mEq/l)	90-110

Preferably, the solution has a pH of 7.3-7.5, an
osmolality of 280-310, and an oncotic pressure of 20-30
25 mm Hg. Osmolality is controlled by concentration of
hemoglobin and of the electrolytes, as well as by the
optional ingredient glucose (preferably 0-30 gm/l).
The oncotic pressure is controlled by the concentration
of the hemoglobin and by its degree of crosslinking.
30 Agents, such as albumin (0-70 gm/l), dextran (0-100
gm/l) and polyethylene glycol (0-25 gm/l) may be added
to increase oncotic pressure. Moreover, to reduce the
degree of methemoglobin formation, anti-oxidant or free
radical scavengers, such as mannitol (0-20 gm/l),

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glutathione (0-4 gm/l), ascorbic acid (0-0.3 gm/l) and vitamin E (0-100 IU/l) may be provided.

5 If a low oxygen affinity mutant hemoglobin is employed, it may be desirable or necessary to adjust the P_{50} of the solution to the preferred level by suitable choice of electrolytes, pH and other characteristics of the composition. Preferably, the
10 final solution has a P_{50} of 24-32 torr under standard physiological conditions.

TABLE 1: NATURAL LOW AFFINITY HEMOGLOBIN MUTANTS

<u>Hemoglobin</u>	<u>Alpha Mutant</u>	<u>P₅₀*</u>		<u>Area of</u> <u>Mutant</u>	<u>Reference</u>
		<u>RBC-Free</u> <u>Hgb</u>	<u>Whole Blood</u> <u>(nl)</u>		
Hirosaki	43(CD1) phe-->leu	n/a		heme	1,2
Torino	43(CD1) phe-->val	n/a		heme	1,3
Moabit	86(F7) leu-->arg		30.6 (26.4-29.2)	heme	4
Titusville	94(G1) asp-->asn	15.8(4.7)		$\bar{a}_1\beta_2$	5

<u>Hemoglobin</u>	<u>Beta Mutant</u>	<u>P₅₀ (mmHg)</u>		<u>Area of</u> <u>Mutant</u>	<u>Reference</u>
		<u>Hgb (nl)</u>	<u>Whole Blood</u> <u>(nl)</u>		
Raleigh	1 val-->acetyl ala	4.0(2.2)		DPG site	6

WO 88/09179

46

PCT/US88/01534

SUBSTITUTE SHEET

SUBSTITUTE SHEET

Connecticut	21(B3) asp-->gly	5.0(2.2)		B-E helices	7
Moscva	24(B6) gly-->asp	14.8(12.6)		B-E helices	8
Rothschild	37(C3) trp-->arg	3.5(2.0)		$\bar{a}_1\beta_2$	9
Hazebrouck	38(C4) thr-->pro		36 (27-29)	$\bar{a}_1\beta_2$	10
Hammersmith	42(CD1) phe-->ser		n/a	heme/ $\bar{a}_1\beta_2$	1,11
Louisville	42(CD1) phe-->leu	24(21)		heme/ $\bar{a}_1\beta_2$	12,13
Sendagi	42(CD1) phe-->val	3.75(3.05)		heme/ $\bar{a}_1\beta_2$	14
Cheverley	45(CD4) phe-->ser		38.7 (28.7)	heme	15
Okaloosa	48(CD7) leu-->arg	0.95(0.7)	30(26)	C-D helices	16
Bologna	61(E5) lys-->met		37.6 (27.0)	B-E helices	17

WO 88/09179

47

PCT/US88/01534

SUBSTITUTE SHEET

Cairo	65(E9) lys-->gln		41(31)	heme	18
Chico	66(E10) lys-->thr	10.1(5.0)	38.0 (27.2)	heme	19
Bristol	67(E11) val-->asp		25.0 (19.0)	heme	20
Seattle	70(E14) ala-->asp		43.5 (28.1)	heme	21,22
Vancouver	73(E17) asp-->tyr	n/a			1,23
Korle-Bu	73(E17) asp-->asn	n/a			1,24
Mobile	73(E17) asp-->val	n/a			
Rahere	82(EF6) lys-->thr	15.5(11.0)		DPG site	26
Pyrgos	83(EF7) gly-->asp			Externa	27
Roseau-Pointe	90(F6) glu-->gly		38(28)	$\alpha_1\beta_2$	28
Agenogi	90(F6) glu-->lys	9.0(6.8)		$\alpha_1\beta_2$	29

W/O 88/09179

PCT/US88/01534

48

SUBSTITUTE SHEET

Caribbean	91(F7)	leu-->arg	28.0(21.0)		heme	30
Kansas	102(G4)	asn-->thr	28.0(9.0)		$\bar{a}_1\beta_2$	31
Beth Israel	102(G4)	asn-->ser		88.0 (26.0)	$\bar{a}_1\beta_2$	32
Saint Mande	102(G4)	asn-->tyr		52 (28)	$\bar{a}_1\beta_2$	33
Richmond	102(G4)	asn-->lys		n/a	$\bar{a}_1\beta_2$	1,34
Burke	107(G9)	gly-->arg	9.3(7.7)		heme	35
Yoshizuka	108(G10)	asn-->asp	12.9(9.0)		$\bar{a}_1\beta_1$	36
Presbyterian	108(G10)	asn-->lys	6.3(2.5)		$\bar{a}_1\beta_1$	37
Peterborough	111(G13)	val-->phe	14.0(9.0)		$\bar{a}_1\beta_1$	38
New York	113(G15)	val-->glu		n/a	G-helix	1,39

WO 88/09179

PCT/US88/01534

Hope	136(H14) gly-->asp	n/a	heme	1,40
Himeji	140(H18) ala-->asp	5.8(4.5)		

* Parenthetical values are that investigator's measured P₅₀ for conventional Hgb A in RBC-free or RBC-bound state, as indicated

WO 88/09179

PCT/US88/01534

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Table 2: Candidate Non-Naturally Occurring Low Affinity Hemoglobin Mutants

alpha chain

5 46 phe-->thr

46 phe-->ser

46 phe-->ala

58 his-->phe

58 his-->trp

10 61 lys-->thr

61 lys-->ser

61 lys-->met

61 lys-->asn

62 val-->leu

15 62 val-->ile

62 val-->phe

62 val-->trp

65 ala-->asp

94 asp-->gln

20 94 asp-->thr

94 asp-->ser

94 asp-->lys

94 asp-->gly

94 asp-->arg

beta chain

21 asp-->ala

21 asp-->ser

45 phe-->ala

30 45 phe-->thr

45 phe-->val

63 his-->phe

63 his-->trp

66 lys-->ser

66 lys-->asn
67 val-->phe
67 val-->trp
67 val-->ile
5 70 ala-->glu
70 ala-->ser
70 ala-->thr
96 leu-->phe
96 leu-->his
10 96 leu-->lys
98 val-->trp
98 val-->phe
102 asn-->asp
102 asn-->glu
15 102 asn-->arg
102 asn-->his
102 asn-->gly
108 asn-->arg
108 asn-->glu

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Table 3: Oxygen Affinity Values for Mutant Hemoglobins

<u>Hemoglobin Mutant</u>	<u>P₅₀ (mmHg)</u>	<u>P₅₀ mutant/P₅₀ wild type</u>
Hgb (beta phe ⁶³)	36.0	7.5
Hgb (beta ile ⁶⁷)	9.4	2.0
Hgb (beta thr ¹⁰²)	11.1	4.6

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CLAIMS

1. A method of supplementing the oxygen-carrying capacity of a patient's blood which comprises administering to the patient a nontoxic composition comprising a cell-free mutant hemoglobin.

2. The method of claim 1 wherein the mutant hemoglobin is a naturally-occurring hemoglobin.

3. The method of claim 1 wherein the mutant hemoglobin is a non-naturally-occurring hemoglobin.

4. The method of claim 1 wherein the cell-free mutant hemoglobin has a P_{50} of at least about 10% greater than that of cell-free conventional hemoglobin under the same conditions.

5. The method of claim 1, wherein the mutant hemoglobin contains a mutation which affects the equilibrium between the R state and the T state of the hemoglobin molecule.

6. The method of claim 1, wherein the mutant hemoglobin contains a mutation of the beta Asn102 (G4) residue.

7. The method of claim 6, wherein the mutant hemoglobin contains a beta Asn102 (G4) -> Thr mutation.

8. The method of claim 1, wherein the mutant hemoglobin contains a His 63 Phe mutation.

9. The method of claim 1, wherein the mutant hemoglobin contains a mutation of an amino acid residue

within 4 angstroms, as determined on a nearest atom-to-nearest atom basis, of the heme moiety.

10. The method of claim 1, wherein the mutant hemoglobin contains a mutation of a first amino acid residue on a first chain which is within 4 angstroms of a second residue on a second and distinct chain, as determined on a nearest atom-to-nearest atom basis, wherein said first and second residues are a part of the $\alpha\beta 2$ or $\alpha 2\beta 1$ interfaces.

11. The method of claim 10, wherein the mutant hemoglobin contains a mutation of beta residue 45 (CD4).

12. The method of claim 10, wherein the mutant hemoglobin contains a mutation of beta residue 70 (E14).

13. The method of claim 1, wherein the mutant hemoglobin contains a mutation of beta 67 Val.

14. The method of claim 1, wherein the mutant hemoglobin contains a mutation of beta 67 Val $\rightarrow$ Ile.

15. The method of claim 4, wherein the mutant hemoglobin is a non-naturally-occurring hemoglobin.

16. The method of claim 1, wherein the composition further comprises an organic phosphate which stabilizes the T state of hemoglobin.

17. The method of claim 1, wherein the mutant hemoglobin contains a mutation wherein another amino

acid residue is converted to cysteine, and wherein said cysteine is cross-linked to another cysteine residue.

5 18. A nontoxic pharmaceutical composition comprising a non-naturally occurring mutant hemoglobin in a pharmaceutically acceptable carrier.

10 19. A recombinant DNA molecule comprising a fused gene, said fused gene comprising a first nucleotide sequence which codes on expression for an alpha globin, and a second nucleotide sequence which codes on expression for at least a 10 amino acid segment of a beta globin.

15 20. The molecule of claim 19, wherein said first and second nucleotide sequences are separated by a first spacer DNA sequence which codes on expression for a sequence of amino acids which provide a selective cleavage site for a site-selective protease.

20 21. The molecule of claim 19, wherein the second nucleotide sequence is positioned so that its first codon is read prior to the reading of the first codon of the first nucleotide sequence in the course of the
25 expression of the fused gene.

22. The molecule of claim 19, wherein the second nucleotide sequence codes on expression for the N-terminal of a beta globin.

30 23. The molecule of claim 19, wherein the first spacer DNA codes for a cleavage site which is selectively cleaved by Factor Xa.

24. A method of producing hemoglobin which comprises (a) producing alpha globin by (i) introducing a recombinant DNA molecule according to claim 19 into a suitable host other than an erythrocyte, (ii) expressing alpha globin as part of a fusion protein, (iii) cleaving said fusion protein at a selective cleavage site to liberate the alpha globin, and (iv) recovering and purifying said alpha globin; (b) obtaining beta globin from a source other than blood; and (c) preparing hemoglobin by combining said alpha and beta globin and a source of heme.

25. A hemoglobin composition comprising cell-free, biologically functional, wholly artificial, non-pyridoxylated hemoglobin in a pharmaceutically acceptable carrier, said hemoglobin being derived from transformed non-erythrocyte cells and said composition being absolutely free of erythrocyte membrane components other than hemoglobin.

26. The hemoglobin composition of claim 25, wherein said hemoglobin has an affinity for oxygen which is lower than that of the conventional hemoglobin depicted in Figure 1.

27. The hemoglobin composition of claim 25 or claim 26, wherein said hemoglobin is an alpha chain hemoglobin mutant.

28. The hemoglobin composition of claim 25, wherein the hemoglobin has the structure of a natural low affinity hemoglobin mutant selected from the group consisting of the mutants identified in Table 1.

29. The method of claim 2 wherein the mutant hemoglobin has the structure of a natural low affinity hemoglobin mutant selected from the group consisting of the mutants identified in Table 1.

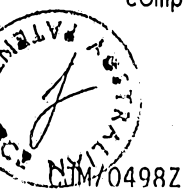
30. The method of claim 3 wherein the mutant hemoglobin is a low affinity hemoglobin mutant selected from the group consisting of mutants having the mutation identified in Table 2 and combinations thereof.

31. A non-naturally occurring low affinity hemoglobin mutant selected from the group consisting of mutants having the mutation identified in Table 2 and combinations thereof.

32. A hemoglobin composition comprising a solution of cell-free, mutant, wholly artificial, non-pyridoxylated hemoglobin in a pharmaceutically acceptable carrier, said solution having a P_{50} under standard physiological conditions of 24-32 torr.

33. The composition of claim 32, wherein said composition further comprises sodium ions, potassium ions and chloride ions.

34. The composition of claim 33. wherein said composition further comprises an oncotic agent.



35. The composition of claim 33 or claim 34, wherein said composition further comprises an antioxidant.

36. Artificial hemoglobin, substantially as hereinbefore described with reference to Example 1.

37. An artificial, low affinity hemoglobin mutant, substantially as hereinbefore described with reference to Example 2.

38. A method for preparing artificial hemoglobin, which method is substantially as hereinbefore described with reference to Example 1.

39. A method for preparing an artificial low affinity hemoglobin mutant, which method is substantially as hereinbefore described with reference to Example 2.

40. A DNA for the expression of the alpha chain of hemoglobin, which DNA is substantially as hereinbefore described with reference to Example 1.

41. A DNA for the expression of a mutant beta chain of hemoglobin, which DNA is substantially as hereinbefore described with reference to Example 2.

42. A composition comprising as a principal component an artificial hemoglobin, which composition is substantially as hereinbefore described with reference to Example 3.

43. A method of supplementing the oxygen-carrying capacity of a patient's blood which comprises administering to the patient a composition as defined in claim 42.

44. A DNA for the expression of the alpha chain of hemoglobin, which DNA is substantially as hereinbefore described with reference to Figure 2c.

DATED this THIRTEENTH day of MARCH 1991

Somatogenetics International, Inc. and Medical Research Council

Patent Attorneys for the Applicant
SPRUSON & FERGUSON



1/5

FIG. 1A.

SEQUENCE: ALPHA

1	GTG CTG TCT CCT GCC GAC AAG ACC AAC GTC AAG GCC GCC TGG	42
	Val Leu Ser Pro Ala Asp Lys Thr Asn Val Lys Ala Ala Trp	
43	GGC AAG GTT GGC GCG CAC GCT GGC GAG TAT GGT GCG GAG GCC	84
	Gly Lys Val Gly Ala His Ala Gly Glu Tyr Gly Ala Glu Ala	
85	CTG GAG AGG ATG TTC CTG TCC TTC CCC ACC ACC AAG ACC TAC	126
	Leu Glu Arg MET Phe Leu Ser Phe Pro Thr Thr Lys Thr Tyr	
127	TTC CCG CAC TTC GAC CTG AGC CAC GGC TCT GCC CAG GTT AAG	168
	Phe Pro His Phe Asp Leu Ser His Gly Ser Ala Gln Val Lys	
169	GGC CAC GGC AAG AAG GTG GCC GAC GCG CTG ACC AAC GCC GTG	210
	Gly His Gly Lys Lys Val Ala Asp Ala Leu Thr Asn Ala Val	
211	GCG CAC GTG GAC GAC ATG CCC AAC GCG CTG TCC GCC CTG AGC	252
	Ala His Val Asp Asp MET Pro Asn Ala Leu Ser Ala Leu Ser	
253	GAC CTG CAC GCG CAC AAG CTT CGG GTG GAC CCG GTC AAC TTC	294
	Asp Leu His Ala His Lys Leu Arg Val Asp Pro Val Asn Phe	
295	AAG CTC CTA AGC CAC TGC CTG CTG GTG ACC CTG GCC GCC CAC	336
	Lys Leu Leu Ser His Cys Leu Leu Val Thr Leu Ala Ala His	
337	CTC CCC GCC GAG TTC ACC CCT GCG GTG CAC GCC TCC CTG GAC	378
	Leu Pro Ala Glu Phe Thr Pro Ala Val His Ala Ser Leu Asp	
379	AAG TTC CTG GCT TCT GTG AGC ACC GTG CTG ACC TCC AAA TAC	420
	Lys Phe Leu Ala Ser Val Ser Thr Val Leu Thr Ser Lys Tyr	
421	CGT	
	Arg	

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2/5

FIG. 1B.

SEQUENCE: beta

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1  GTG CAC CTG ACT CCT GAG GAG AAG TCT GCC GTT ACT GCC CTG 42
   Val His Leu Thr Pro Glu Glu Lys Ser Ala Val Thr Ala Leu

43 TGG GGC AAG GTG AAC GTG GAT GAA GTT GGT GGT GAG GCC CTG 84
   Trp Gly Lys Val Asn Val Asp Glu Val Gly Gly Glu Ala Leu

85 GGC AGG CAG CTG GTG GTC TAC CCT TGG ACC CAG AGG TTC TTT 126
   Gly Arg Leu Leu Val Val Tyr Pro Trp Thr Gln Arg Phe Phe

127 GAG TCC TTT GGG GAT CTG TCC ACT CCT GAT GCT GTT ATG GGC 168
    Glu Ser Phe Gly Asp Leu Ser Thr Pro Asp Ala Val MET Gly

169 AAC CCT AAG GTG AAG GCT CAT GGC AAG AAA GTG CTC GGT GCC 210
    Asn Pro Lys Val Lys Ala His Gly Lys Lys Val Leu Gly Ala

211 TTT AGT GAT GGC CTG GCT CAC CTG GAC AAC CTC AAG GGC ACC 252
    Phe Ser Asp Gly Leu Ala His Leu Asp Asn Leu Lys Gly Thr

253 TTT GCC ACA CTG AGT GAG CTG CAC TGT GAC AAG CTG CAC GTG 294
    Phe Ala Thr Leu Ser Glu Leu His Cys Asp Lys Leu His Val

295 GAT CCT GAG AAC TTC AGG CTC CTG GGC AAC GTG CTG GTC TGT 336
    Asp Pro Glu Asn Phe Arg Leu Leu Gly Asn Val Leu Val Cys

337 GTG CTG GCC CAT CAC TTT GGC AAA GAA TTC ACC CCA CCA GTG 378
    Val Leu Ala His His Phe Gly Lys Glu Phe Thr Pro Pro Val

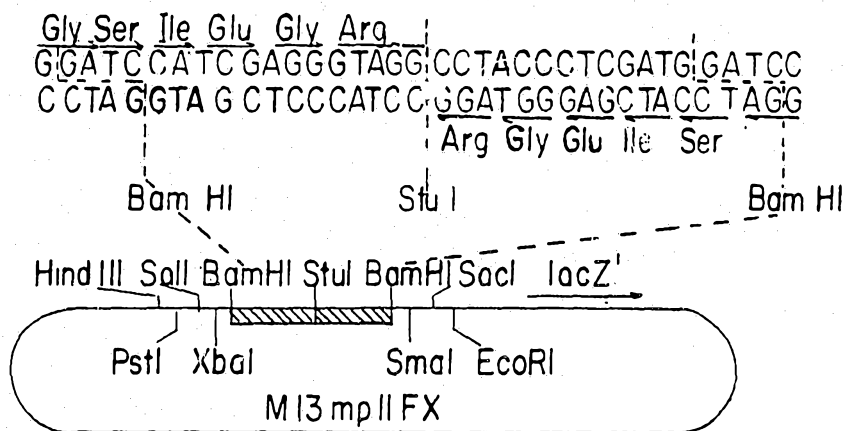
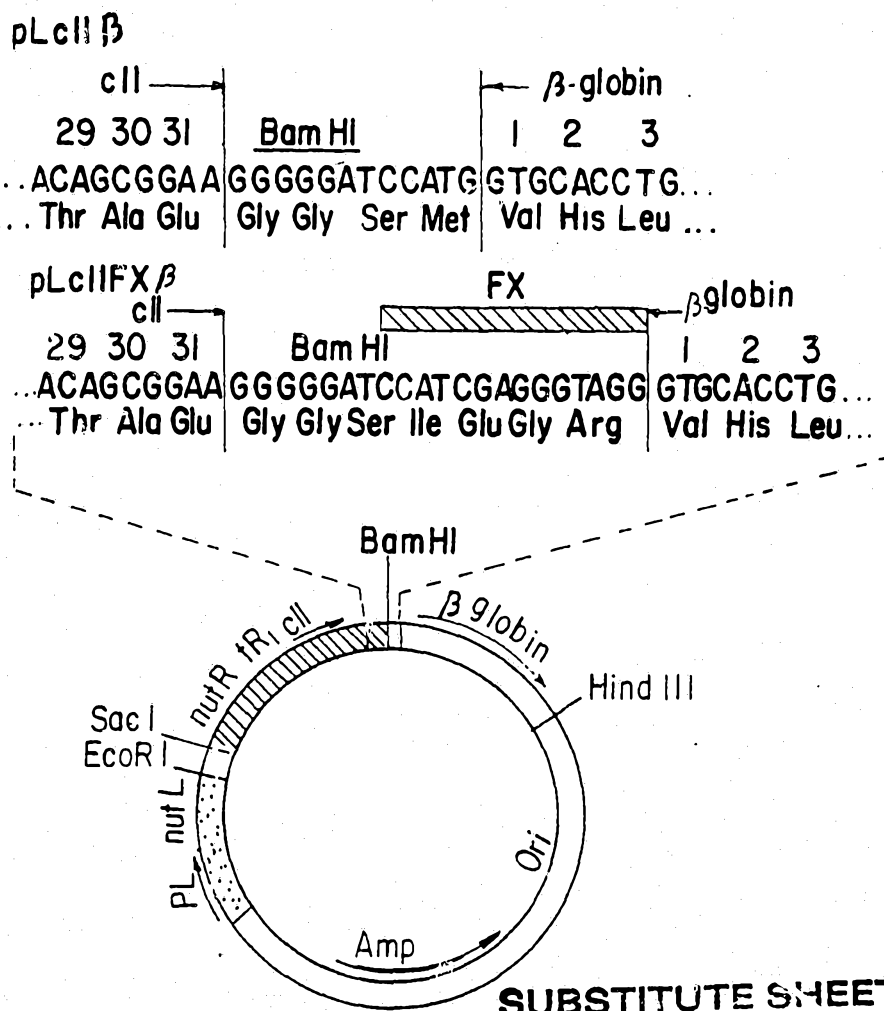
379 CAG GCT GCC TAT CAG AAA GTG GTG GCT GGT GTG GCT AAT GCC 420
    Gln Ala Ala Tyr Gln Lys Val Val Ala Gly Val Ala Asn Ala

421 CTG GCC CAC AAG TAT CAC
    Leu Ala His Lys Tyr His

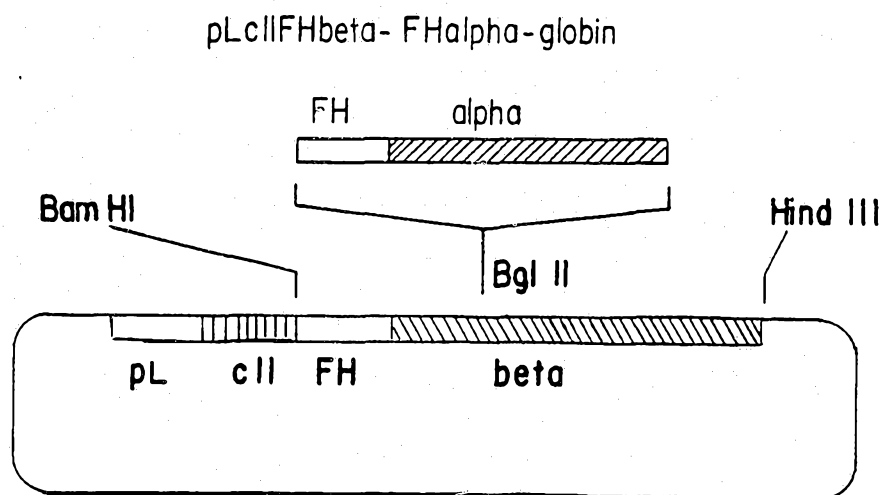
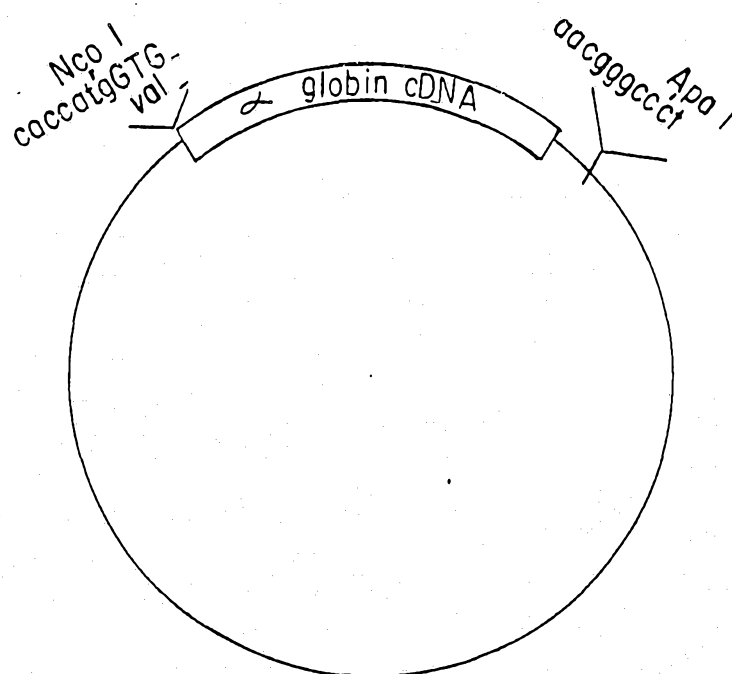
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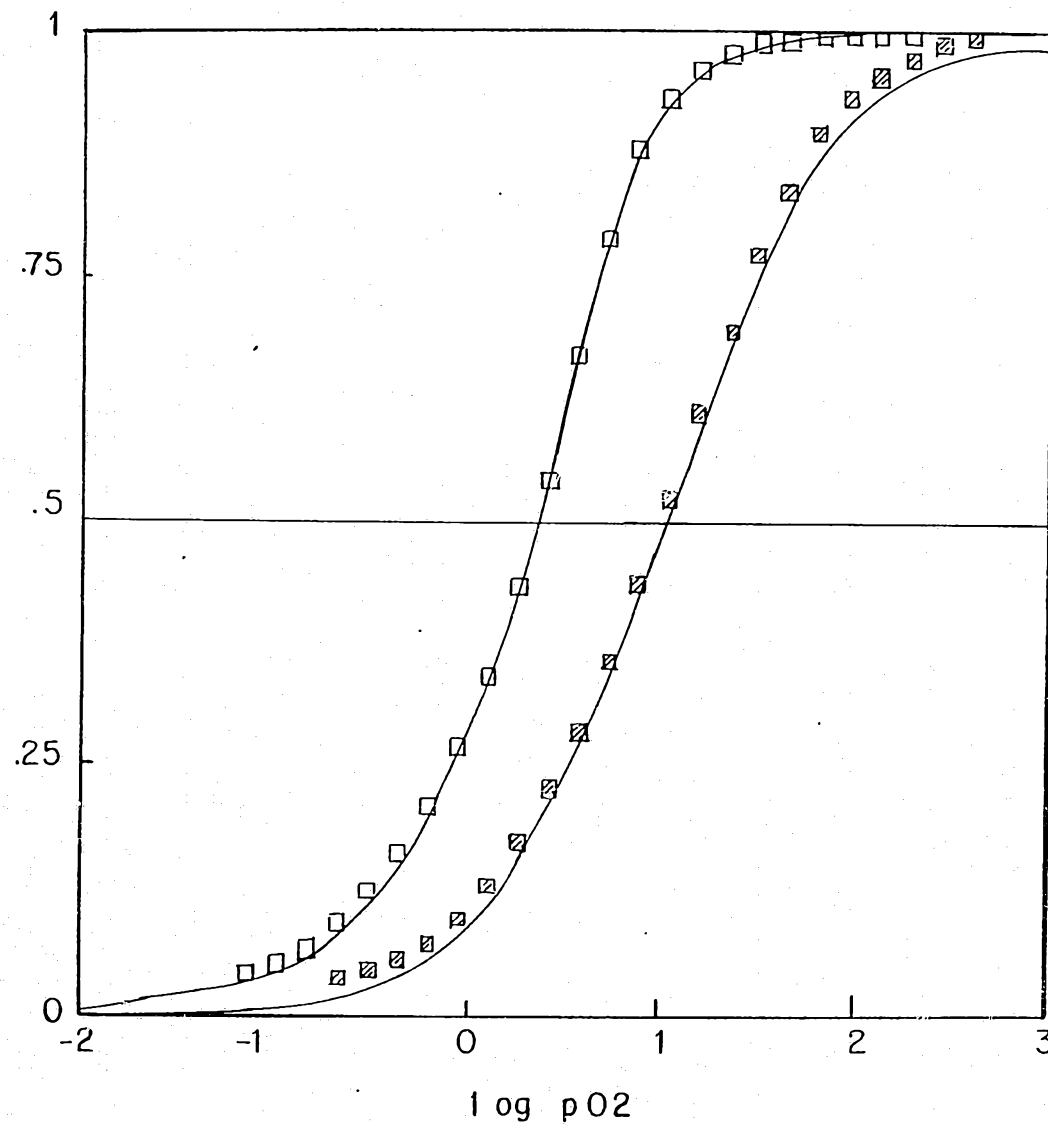
3/5

FIG. 2A.**FIG. 2B.****SUBSTITUTE SHEET**

4/5

FIG. 2C.*FIG. 2D.*

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OXYGEN EQUILIBRIC CURVE FOR HgA
($\alpha_2 \beta_2$ -RECOMBINANT ($\square$) AND Hgb
KANSAS ($\alpha_2 \beta_2$ asn¹⁰²-thr) ($\boxtimes$)
0.1 M HEPES, pH 7.4,
0.1 M NaCl, 25°C.

FIG. 3.

INTERNATIONAL SEARCH REPORT

International Application No. PCT/US88/01534

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) ⁶		
According to International Patent Classification (IPC) or to both National Classification and IPC		
IPC(4): A61K 37/02, C07K 13/00, C12N 15/00, C07H 21/04		
U.S.: 514/6, 536/27, 530/385, 435/68, 70, 172.1		
II. FIELDS SEARCHED		
Minimum Documentation Searched ⁷		
Classification System	Classification Symbols	
U.S.	514/6, 832, 833; 530/385, 808; 435/68, 70, 172.1, 172.2, 172.3, 536/27; 935/10, 27, 28, 34, 47, 60	
Documentation Searched other than Minimum Documentation to the extent that such Documents are Included in the Fields Searched ⁸		
CAS ONLINE, APS, BIOSIS		
III. DOCUMENTS CONSIDERED TO BE RELEVANT ⁹		
Category *	Citation of Document, ¹¹ with indication, where appropriate, of the relevant passages ¹²	Relevant to Claim No. ¹³
X	US, A, 4,529,719 (TYE) 16 July 1985 See entire document.	25, 26, 32
Y	(NAGAI ET AL) "Oxygen binding properties of human mutant hemoglobins synthesized in <u>Escherichia coli</u> ", PNAS USA, issued November 1985, Volume 82, pages 7252-7255, see the entire document.	
Y	(LIEBHABER ET AL) "Cloning and complete nucleotide sequence of human 5'-alpha-globin gene", PNAS USA, issued December 1980, Volume 77, No. 12, pages 7054-7058, see the abstract and Fig. 4.	24
* Special categories of cited documents: ¹⁰ "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier document but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art. "&" document member of the same patent family		
IV. CERTIFICATION		
Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report	
21 JULY 1988	01 SEP 1988	
International Searching Authority	Signature of Authorized Officer	
ISA/US	JACQUELINE M. STONE	

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)

Category *	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No
A	NAGAI ET AL, "Generation of beta-globin by sequence-specific proteolysis of a hybrid protein produced in <u>Escherichia coli</u> ", Nature, issued June 1984, volume 309, pages 810-812, see the entire document.	19-24
A	BONAVENTURA ET AL, "Hemoglobin Kansas, a Human Hemoglobin with a Neutral Amino Acid Substitution and an Abnormal Oxygen Equilibrium", J. Biol. Chem., issued 1968, Volume 243, pages 980-991, see pages 988-990.	1-35
A	DACIE ET AL, "Haemoglobin Hammersmith (beta 42 (CDI)Phe Ser)", Nature, issued November 1967, Volume 216, pages 663-665, see the entire document.	1-35

FURTHER INFORMATION CONTINUED FROM THE SECOND SHEET

V. ☐ OBSERVATIONS WHERE CERTAIN CLAIMS WERE FOUND UNSEARCHABLE ¹

This international search report has not been established in respect of certain claims under Article 17(2) (a) for the following reasons:

1. ☐ Claim numbers _____, because they relate to subject matter ¹² not required to be searched by this Authority, namely:

2. ☐ Claim numbers _____, because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out ¹³, specifically:

3. ☐ Claim numbers _____, because they are dependent claims not drafted in accordance with the second and third sentences of PCT Rule 6.4(a).

VI. ☒ OBSERVATIONS WHERE UNITY OF INVENTION IS LACKING ²

This International Searching Authority found multiple inventions in this international application as follows:

See attachment.

1. ☒ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims of the international application. See attachment.
2. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims of the international application for which fees were paid, specifically claims:

3. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claim numbers:

4. ☐ As all searchable claims could be searched without effort justifying an additional fee, the International Searching Authority did not invite payment of any additional fee.

Remark on Protest

- ☐ The additional search fees were accompanied by applicant's protest.
☐ No protest accompanied the payment of additional search fees.

PCT/US88/01534

Attachment to Form PCT/ISA/210,
Part VI.

- I. Claims 1-18 and 29-35, drawn to a hemoglobin mutant, pharmaceutical compositions thereof and methods of use thereof, classified in class 530 subclass 385 and class 514, subclass 6.
- II. Claims 19-24, drawn to a recombinant DNA molecule and process for producing a hemoglobin using this molecule, classified in class 536, subclass 27 and class 435, subclass 68.
- III. Claims 25-28, drawn to a cell-free hemoglobin composition, classified in class 530, subclass 385.