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(54) Title: BIPHASIC SINGLE-CHAIN INSULIN ANALOGUES

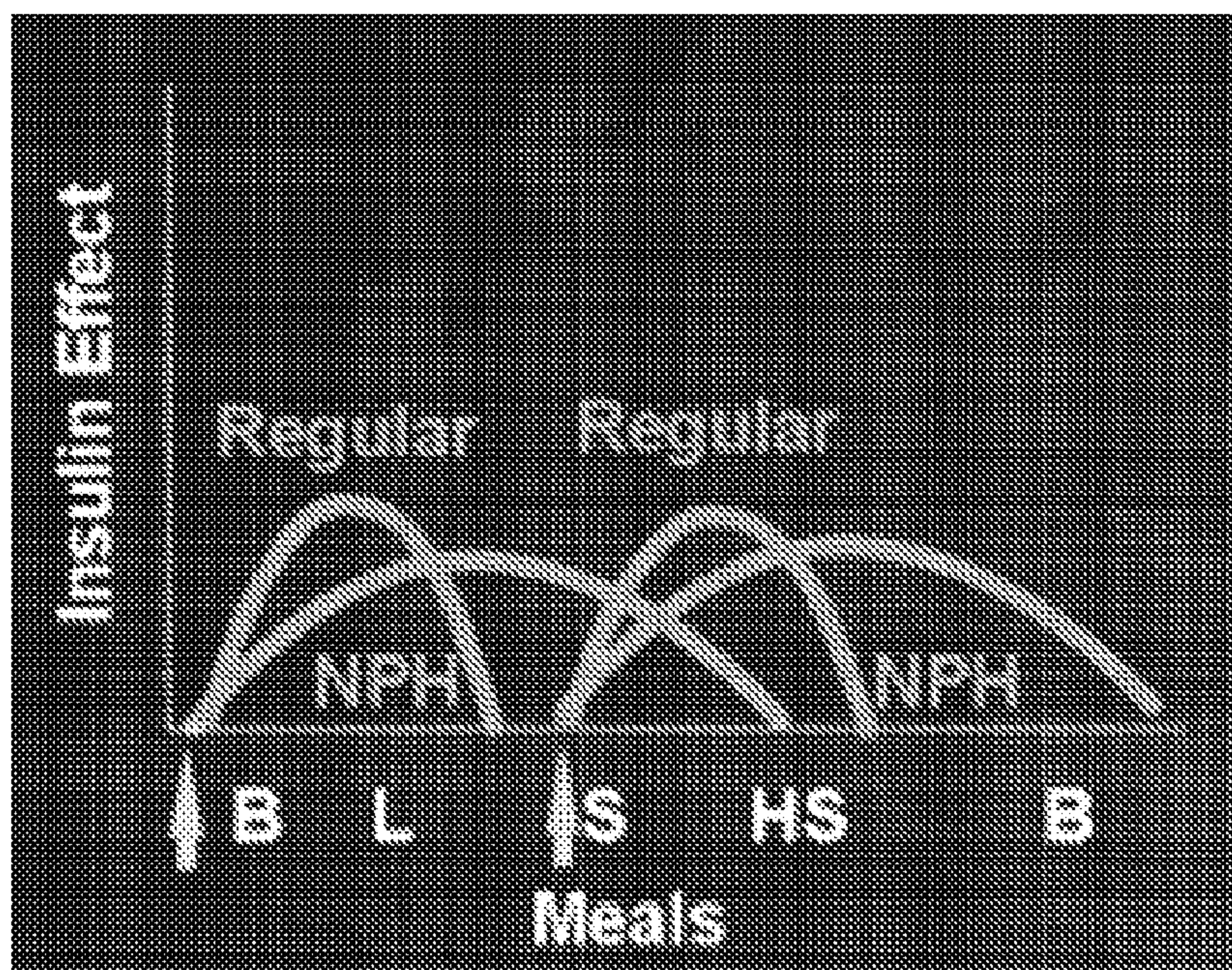


FIGURE 1

(57) **Abrégé/Abstract:**

A single-chain insulin comprises a C-domain of 6 to 11 amino acid residues comprising at least two acidic residues at the N-terminal side of the C-domain and at least two basic residues at the C-terminal side of the C-domain peptide, a basic amino acid residue at the position corresponding to A8 of human insulin, and an acidic amino acid residue at the position corresponding to A14 of human insulin. The C-domain may contain a 2 to 4 amino acid joint region between the acidic and basic residues. Residues C1 and C2 may have a net negative charge of -1 or -2; and the remaining C-domain segment may culminate with two basic residues. A pharmaceutical composition comprises the single-chain insulin, formulated at a pH within the range 7.0 to 8.0, and may be formulated at a concentration of 0.6 mM to 5.0 mM and/or at a strength of U-100 to U-1000.

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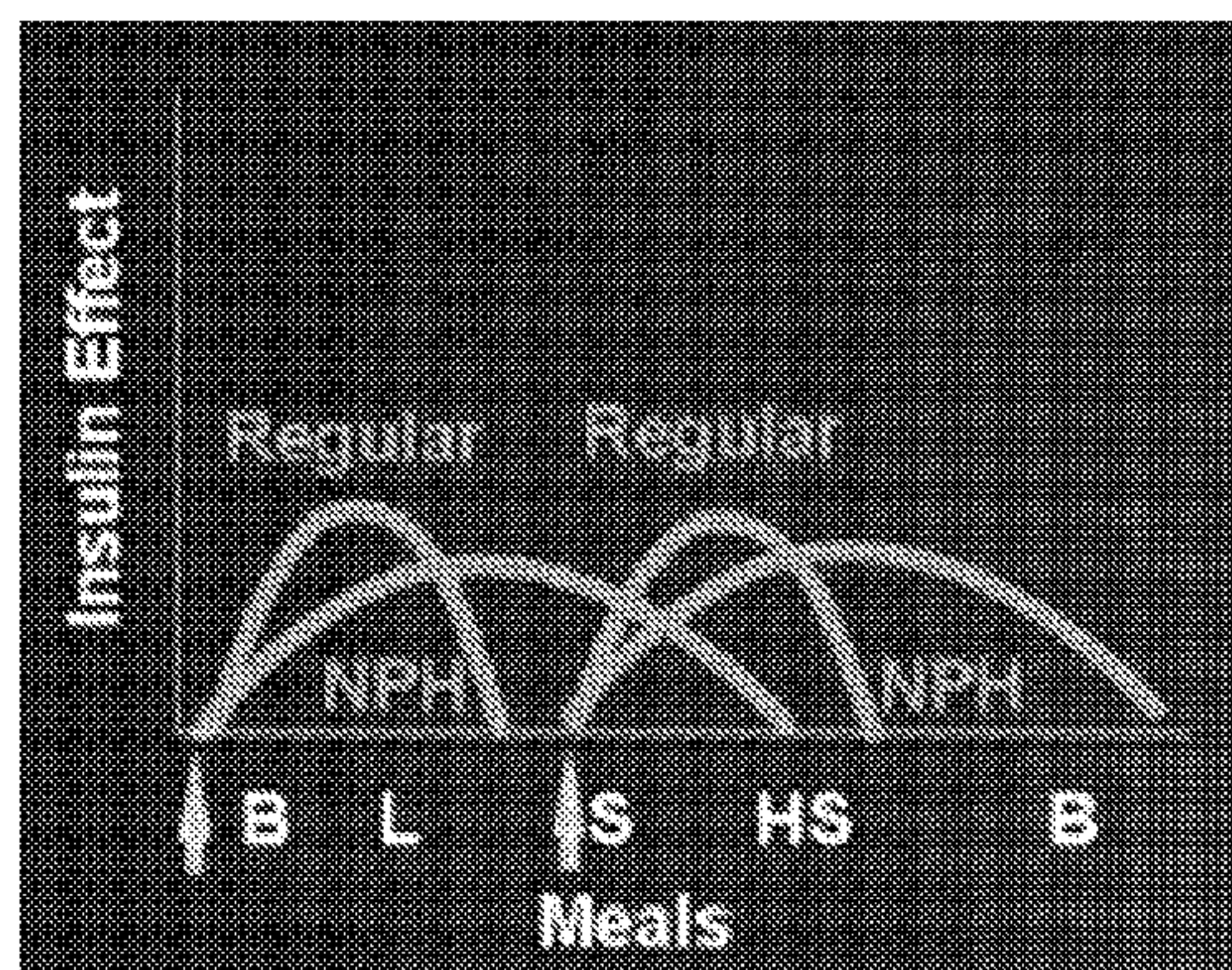


FIGURE 1

(57) **Abstract:** A single-chain insulin comprises a C-domain of 6 to 11 amino acid residues comprising at least two acidic residues at the N-terminal side of the C-domain and at least two basic residues at the C-terminal side of the C-domain peptide, a basic amino acid residue at the position corresponding to A8 of human insulin, and an acidic amino acid residue at the position corresponding to A14 of human insulin. The C-domain may contain a 2 to 4 amino acid joint region between the acidic and basic residues. Residues C1 and C2 may have a net negative charge of -1 or -2; and the remaining C-domain segment may culminate with two basic residues. A pharmaceutical composition comprises the single-chain insulin, formulated at a pH within the range 7.0 to 8.0, and may be formulated at a concentration of 0.6 mM to 5.0 mM and/or at a strength of U-100 to U-1000.

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Biphasic Single-Chain Insulin Analogues

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was made with government support under cooperative agreements awarded by the National Institutes of Health under grant numbers DK040949 and DK074176. The U.S. government may have certain rights to the invention.

BACKGROUND OF THE INVENTION

This invention relates to polypeptide hormone analogues that exhibits enhanced pharmaceutical properties, such as increased thermodynamic stability, augmented resistance to thermal fibrillation above room temperature, decreased mitogenicity, and/or altered pharmacokinetic and pharmacodynamic properties, i.e., conferring a biphasic time course of action relative to (a) a *fast-acting component* similar to soluble formulations of the corresponding prandial or wild-type human hormone and (b) a *prolonged component* similar to microcrystalline NPH formulations of wild-type insulin or insulin analogues. More particularly, this invention relates to insulin analogues consisting of a single polypeptide chain that (i) contains a novel class of foreshortened connecting (C) domains between A and B domains with acidic residues at the first and second positions, (ii) contains an amino-acid substitution at position A8, and (iii) contains an acidic residue at position A14. Of length 6-11 residues, the C domains of this class consist of an N-terminal acidic element and a C-terminal segment basic element similar to that of wild-type proinsulin. The single-chain insulina analogues of the present invention may optionally contain standard or non-standard amino-acid substitutions at other sites in the A or B domains, such as positions B28 and B29 known in the art to confer rapid action.

The engineering of non-standard proteins, including therapeutic agents and vaccines, may have broad medical and societal benefits. Naturally occurring

proteins—as encoded in the genomes of human beings, other mammals, vertebrate organisms, invertebrate organisms, or eukaryotic cells in general—often confer multiple biological activities. A benefit of non-standard proteins would be to achieve selective activity, such as decreased binding to homologous cellular receptors associated with an unintended and unfavorable side effect, such as promotion of the growth of cancer cells. Yet another example of a societal benefit would be augmented resistance to degradation at or above room temperature, facilitating transport, distribution, and use. An example of a therapeutic protein is provided by insulin. Wild-type human insulin and insulin molecules encoded in the genomes of other mammals bind to insulin receptors in multiple organs and diverse types of cells, irrespective of the receptor isoform generated by alternative modes of RNA splicing or by alternative patterns of post-translational glycosylation. Wild-type insulin also binds with lower affinity to the homologous Type 1 insulin-like growth factor receptor (IGF-1R).

An example of a further medical benefit would be optimization of the pharmacokinetic properties of a soluble formulation such that the time course of insulin action has two phases, a rapid phase and a delayed phase (Figure 1). Such a combination of rapid and delayed phases is known in the art to be conferred by mixtures of a solution of zinc insulin analogue hexamers (as provided by, but not limited to, insulin *lispro* and insulin *aspart*) with a micro-crystalline suspension of the same analogue prepared in combination with zinc ions and protamines or protamine-related basic peptides; the latter component is designated in the art as Neutral Protamine Hagedorn (NPH) micro-crystalline suspensions. Pre-mixed insulin products known in the art contain varying ratios of these two components, such as 25% soluble phase and 75% micro-crystalline phase, 30% soluble phase and 70% micro-crystalline phase, or 50% of each phase. Such pre-mixed products are widely used by patients with diabetes mellitus in the developing world due to their ease of use with reduction in the number of subcutaneous injections per day relative to the separate administration of a prandial (rapid-acting) insulin formulation (or prandial insulin analogue formulation) and of a NPH micro-crystalline suspension of wild-type

insulin or insulin analogue. The simplification of insulin regimens of insulin provided by pre-mixed biphasic insulin products has also proven of benefit to patients with diabetes mellitus in affluent societies (i) for whom treatment solely by prandial insulin analogue formulations leads to suboptimal glycemic control or excessive weight gain, (ii) for whom treatment solely by NPH insulin products or basal insulin analog formulations leads to suboptimal glycemic control due to upward excursions in the blood glucose concentration within three hours after a meal, or (iii) patients of the above two classes for whom addition of an oral agent (such as metformin) does not result in satisfactory glycemic control.

Existing biphasic insulin products require a complex and costly method of manufacture due to the post-fermentation and post-purification steps needed to grow NPH micro-crystals. Further, such products suffer from an intrinsic susceptibility of both the soluble and micro-crystalline components to physical and chemical degradation above room temperature. The biphasic pharmacokinetic properties of these pre-mixed products may change with storage of the vials above room temperature due to interchange of insulin molecules between the soluble and micro-crystalline phases. Finally, the use of micro-crystalline suspensions can be associated with uncertainties in dosing as the number of micro-crystals drawn into a syringe can vary from withdrawal to withdrawal even from the same vial.

In light of the above disadvantages of existing biphasic insulin products, the therapeutic and societal benefits of biphasic insulin formulations would be enhanced by the engineering of insulin analogues whose pharmacokinetic properties as a mono-component soluble solution confer a biphasic pattern of insulin action. Additional benefits would accrue if the novel soluble insulin analogue were simpler and less costly to manufacture (*i.e.*, by avoiding the requirement for micro-crystallization) and/or if the novel soluble insulin analogue were more refractory than wild-type insulin to chemical or physical degradation at or above room temperature. Such resistance to degradation above room temperature would be expected to facilitate use in regions of the developing world where electricity and refrigeration are not consistently available. The challenge posed by such degradation is deepened by the

pending pandemic of diabetes mellitus in Africa and Asia. Because fibrillation poses the major route of degradation above room temperature, the design of fibrillation-resistant formulations may enhance the safety and efficacy of insulin replacement therapy in such challenged regions. Still additional therapeutic and societal benefit would accrue if the soluble biphasic insulin analogue should exhibit reduced mitogenicity in assays developed to monitor insulin-stimulated proliferation of human cancer cell lines.

Administration of insulin has long been established as a treatment for diabetes mellitus. A major goal of conventional insulin replacement therapy in patients with diabetes mellitus is tight control of the blood glucose concentration to prevent its excursion above or below the normal range characteristic of healthy human subjects. Excursions below the normal range are associated with immediate adrenergic or neuroglycopenic symptoms, which in severe episodes lead to convulsions, coma, and death. Excursions above the normal range are associated with increased long-term risk of microvascular disease, including retinopathy, blindness, and renal failure. Insulin is a small globular protein that plays a central role in metabolism in vertebrates. Insulin contains two chains, an A chain, containing 21 residues, and a B chain containing 30 residues. The hormone is stored in the pancreatic β -cell as a Zn^{2+} -stabilized hexamer, but functions as a Zn^{2+} -free monomer in the bloodstream. Insulin is the product of a single-chain precursor, proinsulin, in which a connecting region (35 residues) links the C-terminal residue of B chain (residue B30) to the N-terminal residue of the A chain. A variety of evidence indicates that it consists of an insulin-like core and disordered connecting peptide. Formation of three specific disulfide bridges (A6–A11, A7–B7, and A20–B19) is thought to be coupled to oxidative folding of proinsulin in the rough endoplasmic reticulum (ER). Proinsulin assembles to form soluble Zn^{2+} -coordinated hexamers shortly after export from ER to the Golgi apparatus. Endoproteolytic digestion and conversion to insulin occurs in immature secretory granules followed by morphological condensation. Crystalline arrays of zinc insulin hexamers within mature storage granules have been visualized by electron microscopy (EM). Individual residues are indicated by the identity of the amino acid

(typically using a standard three-letter code), the chain and sequence position (typically as a superscript). Pertinent to the present invention is the invention of novel foreshortened C domains of length 6-11 residues, containing an N-terminal acidic motif and a C-terminal basic motif, in place of the 36-residue wild-type C domain characteristic of human proinsulin and in combination with amino-acid substitutions at positions A8 and A14 of the A chain and optionally at positions B28 and B29 of the B chain.

Fibrillation, which is a serious concern in the manufacture, storage and use of insulin and insulin analogues for the treatment of diabetes mellitus, is enhanced with higher temperature, lower pH, agitation, or the presence of urea, guanidine, ethanol co-solvent, or hydrophobic surfaces. Current US drug regulations demand that insulin be discarded if fibrillation occurs at a level of one percent or more. Because fibrillation is enhanced at higher temperatures, patients with diabetes mellitus optimally must keep insulin refrigerated prior to use. Insulin exhibits an increase in degradation rate of 10-fold or more for each 10° C increment in temperature above 25° C; accordingly, guidelines call for storage at temperatures < 30° C and preferably with refrigeration. The NPH micro-crystalline component of existing biphasic insulin product is susceptible to fibrillation above room temperature as well as a distinctive mode of chemical degradation due to proteolytic cleavage within the A chain; such cleavage inactivates the insulin or insulin analogue.

The above cleavage of the insulin A chain in NPH micro-crystals is representative of a process involving the breakage of chemical bonds. Such breakage can lead to loss or rearrangement of atoms within the insulin molecule or the formation of chemical bonds between different insulin molecules, leading to formation of polymers. Whereas cleavage of the A chain in NPH micro-crystals is thought to occur on the surface of the folded state, other changes in chemical bonds are mediated in the unfolded state of the protein or in partially unfolded forms of the protein, and so modifications of insulin that augment its thermodynamic stability also are likely to delay or prevent chemical degradation. It is therefore a desirable property of an insulin analogue that its free energy of denaturation (as typically

measured by circular dichroism at a helix-sensitive wavelength as a function of the concentration of a chemical denaturant) should be equal to or greater than that of wild-type insulin or equal to or greater than that of a prandial (rapid-acting) insulin analogue in current clinical use.

Insulin is also susceptible to physical degradation. The present theory of protein fibrillation posits that the mechanism of fibrillation proceeds via a partially folded intermediate state, which in turn aggregates to form an amyloidogenic nucleus. In this theory, it is possible that amino-acid substitutions that stabilize the native state may or may not stabilize the partially folded intermediate state and may or may not increase (or decrease) the free-energy barrier between the native state and the intermediate state. Therefore, the current theory indicates that the tendency of a given amino-acid substitution in the two-chain insulin molecule to increase or decrease the risk of fibrillation is highly unpredictable. Models of the structure of the insulin molecule envisage near-complete unfolding of the three alpha-helices (as seen in the native state) with parallel arrangements of beta-sheets forming successive stacking of B-chains and successive stacking of A-chains; native disulfide pairing between chains and within the A-chain is retained. Such parallel cross-beta sheets require substantial separation between the N-terminus of the A-chain and C-terminus of the B-chain (>30 Å), termini ordinarily in close proximity in the native state of the insulin monomer (<10 Å). Marked resistance to fibrillation of single-chain insulin analogues with foreshortened C-domains is known in the art and thought to reflect a topological incompatibility between the splayed structure of parallel cross-beta sheets in an insulin protofilament and the structure of a single-chain insulin analogue with native disulfide pairing in which the foreshortened C-domain constrains the distance between the N-terminus of the A-chain and C-terminus of the B-chain to be unfavorable in a protofilament. A ribbon model of a single-chain insulin analogue is shown in Figure 2; a space-filling model of the insulin moiety is shown in Figure 3 to highlight the role of the engineered connecting domain (C domain; stick representation in Fig. 3).

The present invention was motivated by the medical and societal needs to engineer a biphasic single-chain insulin analogue in a soluble and monophasic formulation at neutral pH intended for twice-a-day injection, i.e., on a schedule similar to that of current pre-mixed regular-NPH biphasic insulin products. Our single-chain design is intended to combine (i) resistance to degradation with (ii) substantial in vivo hypoglycemic potency with (iii) reduced cross-binding to IGF-1R and (iv) intrinsic biphasic pharmacokinetics and pharmacodynamics in the absence of a component consisting of a micro-crystalline suspension. It would be desirable, therefore, to invent single-chain insulin analogue that, as a soluble protein solution at neutral pH, exhibits biphasic pharmacokinetic- and pharmacodynamics properties on subcutaneous injection such that both rapid-onset of action and a prolonged tail of action are achieved leading to an overall profile that resembles those of premixed products as exemplified by “Humalog® Mix75/25” or “NovaMix® 30.” Biphasic insulin analog formulations of the present invention will therefore provide simplified twice-a-day bolus-basal regimens that will be of clinical advantage in the developed and developing world. Single-chain biphasic insulin analogue formulations may also be initiated in insulin-naïve patients not well controlled on metformin, a first-line oral agent widely used in the treatment of T2DM. The mechanism of biphasic action of current regular-NPH premixed products, based on pharmacokinetic properties of the two components, is shown in schematic form in Figure 4A. While not wishing to be constrained by theory, a possible mechanism of biphasic pharmacokinetics by analogies of the present invention is shown in schematic form in Figure 4B.

We envisage that the products of the present invention will disproportionately benefit patients in Western societies whose compliance with more complex regimens is uncertain. It is known in the art that health-care outcomes—and long-term adherence to prescribed regimens in chronic diseases such as T2DM and the metabolic syndrome—are a complex function of socioeconomic status, formal education, family structure, and cultural belief systems. Indeed, these societal issues are of increasing concern given the growing burden of obesity and T2DM among under-represented minorities, including African-Americans, Hispanic and indigenous

Americans. Single-chain biphasic insulin analogue formulations of the present invention are therefore intended to benefit insulin-requiring T1DM and T2DM patients who have inadequate glycemic control with basal-only insulin therapy but for whom a full basal-bolus regimen is impractical.

SUMMARY OF THE INVENTION

It is, therefore, an aspect of the present invention to provide single-chain insulin analogues that provide biphasic pharmacokinetic and pharmacodynamics properties on subcutaneous injection. The analogues of the present invention contain Histidine at position B10 and so circumvent concerns regarding carcinogenesis that is associated with an acidic substitution (Aspartic Acid or Glutamic Acid) at this position. It is an additional aspect of the present invention that absolute *in vitro* affinities of the single-chain insulin analogue for IR-A and IR-B are in the range 5-100% relative to wild-type human insulin and so unlikely to exhibit prolonged residence times in the hormone-receptor complex.

The above combination of features is conferred by a novel C-domain design wherein a foreshortened connecting polypeptide (length 6-11 residues) contains an N-terminal acidic element (residues C1 and C2), a flexible joint or hinge (C3 and C4), and C-terminal segment containing a pair of basic residues analogous to those observed in natural proinsulins (C5 and C6). An upper limit of 11 for the C-domain length was chosen to be below the 12-residue IGF-I-derived linker described in a chimeric insulin analogue with enhanced IGF-1R-binding activity (Kristensen, C., et al. 1995). A lower limit of 4 was chosen to preserve the acidic motif at the N-terminal portion of the connection domain (such as, but not restricted to, Glu-Glu) and basic motif at the C-terminal portion of the connection domain (such as, but not restricted to, Arg-Arg). Although not wishing to be constrained by theory, we imagine that the two-residue acidic residue introduces unfavorable electrostatic repulsion on binding of the analogue to IGF-1R but is well tolerated by insulin receptor isoforms. Also without wishing to be constrained by theory, we further

imagine that the C-terminal basic motif contributes to partial subcutaneous aggregation rather than a mere tether or space element.

In general, the present invention provides a single-chain insulin analogue comprising a C-domain of the present invention and a modified A-chain containing substitutions at position A8 and A14. The present invention thus pertains to a novel class of single-chain insulin analogues wherein the connecting domain (C domain) is of length 4-11 and consists of two elements. The N-terminal element consists of the first two residues (designated C1 and C2, corresponding to residues B31-B32 of an extended insulin B-chain) wherein C1 and C2 contain at least one acidic side chain and a net formal electrostatic charge at pH 7.4 of -1 or -2. The C-terminal element contains two basic residues as Arg-Arg, Lys-Lys, Arg-Lys or Lys-Arg. For four-residue connecting domains, the sequences of the present invention would thus include, but not be limited to, Glu-Glu-Arg-Arg, Glu-Ala-Arg-Arg, Ala-Glu-Arg-Arg, Asp-Glu-Arg-Arg, Glu-Glu-Lys-Arg, Glu-Glu-Arg-Lys, and Glu-Glu-Lys-Lys. Between the N- and C-terminal elements in the case of connecting domains of length greater than 4 (i.e., in the range 5-11), the connection domain contains a flexible joint. In the example of a six-residue connecting domain, such sequences may contain at positions C3 and C4 Gly-Pro, Ser-Pro, Ala, Pro, Gly-Ser, Ser-Ser, Gly-Gly, or Ala-Ala but the scope of the present invention is not limited to these possibilities. The A-chain contains a basic substitution at A8 (Lysine, Arginine, or Histidine) and a substitution at A21 (Gly, Ala, or Ser) to avoid acid-catalyzed deamidation or other modes of Asn-related chemical degradation. In one example the B-chain also contains substitutions Lys^{B29}→Arg to avoid Lys-specific proteolytic cleavage in the course of biosynthesis in yeast. The analogues of the present invention also contain a substitution at position A8 (Ala, Glu, Gln, His, Lys, or Arg), intended to enhance stability and activity; and a substitution at A14 (Glu), intended to avoid the reverse-hydrophobic effect presumably incurred by the wild-type TyrA14 and to provide an additional negative charge. Other possible substitutions at position A14 are also envisioned.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

FIGURE 1. Schematic goal of biphasic insulin products. Original implementation used wild-type insulin (regular and NPH) whereas current products employ prandial insulin analogs. This figure was obtained from R. Beaser & S. Braunstein, MedScape Multispecialty (Education/CME section; 2009) (<http://www.medscape.org/viewarticle/708784>).

FIGURE 2. Ribbon model of 57-residue SCI. α -Helices are shown in red (outside) and yellow (inside), and the B24-B28 β -strand in blue (arrow). The three disulfide bridges (cystines) are shown (asterisks). The C-domain (Sequence GGGPRR) is well ordered (Hua, Q.X., et al. *J. Biol. Chem.* 283, 14703-16 (2008)).

FIGURE 3. Molecular structure of the 57-residue SCI platform. The six-residue C-domain (sticks; *turquoise*) provides a tether between A- and B domains (space-filling representation). The surface is color-coded according to electrostatic potential in standard GRASP format (*red*, electronegative; *purple*, electropositive; and *white*, neutral). This image was obtained from PDB entry 2jzq, based upon NMR studies in the Weiss laboratory (Hua, Q.X., et al. *J. Biol. Chem.* 283, 14703-16 (2008)).

FIGURE 4. Old and new paradigms. (A) Current biphasic insulin products contain a soluble phase (zinc hexamers; green) and an insoluble phase (NPH microcrystalline suspension; blue). (B) Proposed new paradigm seeks to exploit coupled equilibria among monomeric insulin analog (I), zinc-free dimer (I_2), zinc-stabilized and/or zinc-free hexamers (I_6), and soluble aggregates (I_{6n}). Not shown: TR transition.

FIGURE 5. Over-expression of Thermalin-biphasic (versions 1 and 2) in yeast *P. pastoris*. Coomassie-stained SDS-PAGE gels: (A) SCI-57PE (lanes b-d) relative to molecular-mass markers (a). (B) SCI-57DP (lane g) relative to His^{A8}-miniproinsulin (MPI) as positive control (f) and standards (e). The SCIs migrate $\approx$ 6 kilo-Daltons

(K_d); mini-proinsulins near 5.8 Kd.

FIGURE 6. Diabetic rats (time 0 blood glucose of 400 ± 20 mg/dl) were injected s.q. with 1 unit of the indicated insulin analog/300 g body weight. A. (✕) Humalog (*lispro*) vs. (△) Humalog 25/75-Premix vs. (▲) SCI-57PE (labeled SCI-1 in the figure) fresh vs. (◆) SCI-57DP (labeled SCI-2) fresh vs. (●) diluent. B. Decrease in blood glucose during the first 1st hour post-injection (same symbol codes). The number of rats in each group (n) was as indicated; error bars, standard errors.

FIGURE 7. Initial rate of decrease in [blood glucose] following 1 unit s.q. injection of the indicated insulin analog: + denotes SCI-57PE (labeled SCI-1) agitated at 45 °C for 25 days; ++denotes SCI-57DP (labeled SCI-2) agitated at 45 °C for 57 days. *p<0.05 compared to all other insulin. ** p<0.05 compared to pre-mixed Lispro 75/25. Data pertain to first hour post-injection (see Fig. 8B); error bars, standard errors.

FIGURE 8. Diabetic rats (time 0 blood glucose of 410 ± 20 mg/dl) were injected s.q. with 1 unit of the indicated analog/300 g body weight. A. Fresh samples: (◆) SCI-57DP (labeled SCI-2), (△) Lantus (*glargine*), (✕) Humalog (*lispro*), and (●) diluent. A. Fresh insulin. B. Effects of agitation at high temperature: (◆) fresh SCI-57DP vs. (□) SCI-57DP agitated at 45°C for 57 days vs. (○) Lantus (*glargine*) agitated at 45°C for 11 days.

FIGURE 9. Lilly Co²⁺-EDTA sequestration assay: normalized absorbance at visible wavelength 574 nm is shown as a function of time following addition of EDTA (in 10-fold molar excess) to a solution of R₆ cobalt insulin hexamers or SCI-1 hexamers at 25 °C. Wild-type insulin (black line): mono-exponential transition with time constant $6.3(\pm 0.1)$ min. SCI-1 (green line): biphasic transition with time constants $0.9(\pm 0.1)$ min (fast phase) and $14.1(\pm 0.1)$ min (slow phase); $r^2=0.998$. Proteins were 3.5 mg/ml in 50 mM Tris-HCl (pH 7.4) containing 1 mM NaSCN, 0.2 mM CoCl₂, and 50 mM phenol.

DETAILED DESCRIPTION OF THE INVENTION

The present invention is directed toward a single-chain insulin analogue that provides protracted duration of action, a ratio of IR-A/IR-B receptor-binding affinities similar to that of wild-type insulin with absolute affinities in the range 5-100% (the lower limit chosen to correspond to proinsulin), increased discrimination against IGF-1R, presumed augmented resistance to chemical degradation at position A21 (due to substitution of Asn by Gly, Ala or Ser), presumed augmented resistance to fibrillation above room temperature (due to single-chain topology), and presumed increased thermodynamic activity (due in part to substitution of Thr^{A8} by a basic side chain; Arg, Lys, His, Orn).

It is a feature of the present invention that biphasic absorption kinetics from a subcutaneous depot may be generated by a single-chain insulin analogue when formulated as a clear and soluble monophasic solution of the protein. Conventional premixed products, as known in the art, represent an extreme end of a continuum of possible coupled equilibria between states of self-assembly (Fig. 4A). Alternative strategies to provide a combination of rapid and delayed absorption are envisaged that depend on the rate constants governing these coupled equilibria and relative thermodynamic stabilities as illustrated in schematic form Figure 4B. Molecular implementation of this strategy requires an insulin analog that is (i) ultra-stable as a zinc-free monomer and dimer and (ii) also amenable to forming stable zinc-mediated hexamers susceptible to higher-order aggregation (soluble in the vial or pen but possibly insoluble in the depot). Although not wishing to be constrained by theory, the zinc-free monomers and dimers could provide the prandial component; the zinc-stabilized hexamer aggregates would provide the long-acting component. Also not wishing to be constrained by theory, it is a further possibility that single-chain insulin analogues, when present as monomeric protein molecules in the blood stream, may exhibit biphasic signaling properties at target cells through intrinsic features of their hormone-receptor signaling complexes, such that their pharmacodynamics properties may in this way mimic the biphasic pharmacokinetic properties of existing regular-NPH pre-mixed products.

It is a feature of the present invention that the isoelectric point of the single-chain analogue is between 6.8 and 7.8 such that a soluble formulation is feasible under neutral conditions (pH 7.0-8.0) either in the presence of 2-3 zinc ions per six protein monomers or in the presence of less than 2 zinc ions per six protein monomers such that hexamer assembly would be incomplete. It is thus a feature of the present invention that the single-chain insulin analogue retain a competence to undergo zinc-ion-dependent formation of protein hexamers analogous to the classical zinc insulin hexamer known in the art as T_6 insulin hexamer, $T_3R_3^f$ insulin hexamer, or R_6 insulin hexamer.

It is also envisioned that single-chain analogues may also be made with A- and B-domain sequences derived from animal insulins, such as porcine, bovine, equine, and canine insulins, by way of non-limiting examples. In addition or in the alternative, the insulin analogue of the present invention may contain a deletion of residues B1-B3 or may be combined with a variant B chain lacking Lysine (e.g., LysB29 in wild-type human insulin) to avoid Lys-directed proteolysis of a precursor polypeptide in yeast biosynthesis in *Pichia pastoris*, *Saccharomyces cerevisiae*, or other yeast expression species or strains. The B-domain of the single-chain insulin of the present invention may optionally contain non-standard substitutions, such as D-amino-acids at positions B20 and/or B23 (intended to augment thermodynamic stability, receptor-binding affinity, and resistance to fibrillation), a halogen modification at the 2 ring position of Phe^{B24} (i.e., *ortho*-F-Phe^{B24}, *ortho*-Cl-Phe^{B24}, or *ortho*-Br-Phe^{B24}; intended to enhance thermodynamic stability and resistance to fibrillation), 2-methyl ring modification of Phe^{B24} (intended to enhance receptor-binding affinity), and/or introduction of iodo-substitutions within the aromatic ring of Tyr^{B16} and/or Tyr^{B26} (3-*mono*-iodo-Tyr or [3, 5]-*di*-iodo-Tyr); intended to augment thermodynamic stability and receptor-binding activity). It is also envisioned that Thr^{B27}, Thr^{B30}, or one or more Serine residues in the C-domain may be modified, singly or in combination, by a monosaccharide adduct; examples are provided by O-linked N-acetyl- β -D-galactopyranoside (designated GalNAc-O β -Ser or GalNAc-O β -Thr), O-linked α -D-mannopyranoside (mannose-O β -Ser or mannose-O β -Thr), and/or

α -D-glucopyranoside (glucose-O β -Ser or glucose-O β -Thr).

Furthermore, in view of the similarity between human and animal insulins, and use in the past of animal insulins in human patients with diabetes mellitus, it is also envisioned that other minor modifications in the sequence of insulin may be introduced, especially those substitutions considered “conservative.” For example, additional substitutions of amino acids may be made within groups of amino acids with similar side chains, without departing from the present invention. These include the neutral hydrophobic amino acids: Alanine (Ala or A), Valine (Val or V), Leucine (Leu or L), Isoleucine (Ile or I), Proline (Pro or P), Tryptophan (Trp or W), Phenylalanine (Phe or F) and Methionine (Met or M). Likewise, the neutral polar amino acids may be substituted for each other within their group of Glycine (Gly or G), Serine (Ser or S), Threonine (Thr or T), Tyrosine (Tyr or Y), Cysteine (Cys or C), Glutamine (Glu or Q), and Asparagine (Asn or N). Basic amino acids are considered to include Lysine (Lys or K), Arginine (Arg or R) and Histidine (His or H). Acidic amino acids are Aspartic acid (Asp or D) and Glutamic acid (Glu or E). Unless noted otherwise or wherever obvious from the context, the amino acids noted herein should be considered to be L-amino acids. Standard amino acids may also be substituted by non-standard amino acids belong to the same chemical class. By way of non-limiting example, the basic side chain Lys may be replaced by basic amino acids of shorter side-chain length (Ornithine, Diaminobutyric acid, or Diaminopropionic acid). Lys may also be replaced by the neutral aliphatic isostere Norleucine (Nle), which may in turn be substituted by analogues containing shorter aliphatic side chains (Aminobutyric acid or Aminopropionic acid).

The amino-acid sequence of human proinsulin is provided, for comparative purposes, as SEQ ID NO: 1.

SEQ ID NO: 1 (human proinsulin)

Phe-Val-Asn-Gln-His-Leu-Cys-Gly-Ser-His-Leu-Val-Glu-Ala-Leu-Tyr-Leu-Val-Cys-Gly-Glu-Arg-Gly-Phe-Phe-Tyr-Thr-Pro-Lys-Thr-Arg-Arg-Glu-Ala-Glu-Asp-Leu-Gln-Val-Gly-Gln-Val-Glu-Leu-Gly-Gly-Gly-Pro-Gly-Ala-Gly-Ser-Leu-

Gln-Pro-Leu-Ala-Leu-Glu-Gly-Ser-Leu-Gln-Lys-Arg-Gly-Ile-Val-Glu-Gln-Cys-Cys-Thr-Ser-Ile-Cys-Ser-Leu-Tyr-Gln-Leu-Glu-Asn-Tyr-Cys-Asn

The amino-acid sequence of the A chain of human insulin is provided as SEQ ID NO: 2.

SEQ ID NO: 2 (human A chain)

Gly-Ile-Val-Glu-Gln-Cys-Cys-Thr-Ser-Ile-Cys-Ser-Leu-Tyr-Gln-Leu-Glu-Asn-Tyr-Cys-Asn

The amino-acid sequence of the B chain of human insulin is provided as SEQ ID NO: 3.

SEQ ID NO: 3 (human B chain)

Phe-Val-Asn-Gln-His-Leu-Cys-Gly-Ser-His-Leu-Val-Glu-Ala-Leu-Tyr-Leu-Val-Cys-Gly-Glu-Arg-Gly-Phe-Phe-Tyr-Thr-Pro-Lys-Thr

The amino-acid sequence of the modified B chain of KP-insulin (insulin *lispro*, the active component of Humalog®; Eli Lilly and Co.) is provided as SEQ ID NO: 4.

SEQ ID NO: 4 (human “KP” B chain)

Phe-Val-Asn-Gln-His-Leu-Cys-Gly-Ser-His-Leu-Val-Glu-Ala-Leu-Tyr-Leu-Val-Cys-Gly-Glu-Arg-Gly-Phe-Phe-Tyr-Thr-Lys-Pro-Thr

SEQ ID NO 5 provides the amino-acid sequence of a single-chain insulin analogue that has been previously disclosed (Hua, Q.X., et al. *J. Biol. Chem.* 283, 14703-16 (2008)) and whose structure is shown in Figures 1 and 2. Unlike the analogues of the present invention, this sequence lacks acid residues at positions A14, C1 and C2 and contains an acidic residue at position B10; the resulting single-chain insulin analogue does not exhibit the desired biphasic pharmacodynamics properties of the present invention.

The amino-acid sequence of single-chain insulin analogues of the present invention are in part given in SEQ ID NO 6-19, corresponding to single-chain insulin analogs. These sequences employ standard single-letter code, such that Ala is represented by A, Cysteine is represented by C, Aspartic Acid is represented by D, Glutamic Acid is represented by E, and so forth as is known in the art. Elements in red indicate sequences or substitutions not present in wild-type insulin or wild-type proinsulin. Dashes in SEQ ID NO 13 and 19 indicate deletion of N-terminal residues B1-B3 (designated *des*-B1-B3 analogues).

<u>SEQ ID NO: 5</u> FVNQHLCGSDLVEALYLVCGERGFFYTDPTGGGPRRGIVE QCCHSICSLYQLENYCN
<u>SEQ ID NO: 6</u> FVNQHLCGSHLVEALYLVCGERGFFYTDPTGGGPRRGIVE QCCHSICSLQLENYCN
<u>SEQ ID NO: 7</u> FVNQHLCGSHLVEALYLVCGERGFFYTDPTGEGPRRGIVE QCCHSICSLQLENYCN
<u>SEQ ID NO: 8</u> FVNQHLCGSHLVEALYLVCGERGFFYTDPTTEEGPRRGIVE QCCHSICSLQLENYCN
<u>SEQ ID NO: 9</u> FVNQHLCGSHLVEALYLVCGERGFFYTDPTTEEGPRRGIVE QCCHSICSWEQLENYCN
<u>SEQ ID NO: 10</u> FVNQHLCGSHLVEALYLVCGERGFFYTPETEEGPRRGIVE QCCHSICSLQLENYCN
<u>SEQ ID NO: 11</u> FVNQHLCGSHLVEALYLVCGERGFFYTPRTEEGPRRGIVE QCCHSICSLQLENYCN

<u>SEQ ID NO: 12</u> FVNQHLCGSHLVEALYLVCGERGFFYTEPTTEEGPRRGIVE QCC ~~H~~ SICSLEQLENYCN
<u>SEQ ID NO: 13 (<i>des</i>-B1-B3)</u> ---QHLCGSHLVEALYLVCGERGFFYTPETEEGPRRGIVEQC CHSICSLEQLENYCN
<u>SEQ ID NO: 14</u> FVNQHLCGSHLVEALYLVCGERGFFYTDPTTEEGPRRGIVE QCC ~~H~~ SICSLEQLENYCN
<u>SEQ ID NO: 15</u> FVNQHLCGSHLVEALYLVCGERGFFYTDPTTEEGRRGIVEQ CCHSICSLEQLENYCN
<u>SEQ ID NO: 16</u> FVNQHLCGSHLVEALYLVCGERGFFYTDPTTEERRGIVEQC CHSICSLEQLENYCN
<u>SEQ ID NO: 17</u> FVNQHLCGSHLVEALYLVCGERGFFYTDPTTEERGIVEQCC H ~~S~~ ICSLEQLENYCN
<u>SEQ ID NO: 18</u> FVNQHLCGSHLVQALYLVCGERGFFYTPETEEGPRRGIVE QCC ~~H~~ SICSLEQLENYCN
<u>SEQ ID NO: 19 (<i>des</i>-B1-B3)</u> ---QHLCGSHLVEALYLVCGERGFFYTDPTTEEGPRRGIVEQC CHSICSLEQLENYCN

Amino-acids sequence of single-chain insulin analogues of the present invention are also given in SEQ ID NO 20-34, corresponding to single-chain insulin analogs with optional elements at positions indicated by X₁, X₂, and so forth; these positions are indicated in green. As above, elements in red indicate sequences or substitutions that are otherwise not present in wild-type insulin or wild-type proinsulin. Dashes in SEQ ID NO 13 and 19 indicate deletion of N-terminal residues

B1-B3 (designated *des*-B1-B3 analogues).

<u>SEQ ID NO: 20</u> FVNQHLCGSHLVEALYLVCGERGFFYTX ₁ PTESPRRGIVEQ CCX ₂ SICSLX ₃ QLENYCN
<u>SEQ ID NO: 21</u> FVNQHLCGSHLVEALYLVCGERGFFYTX ₁ PTSEGPRRGIVE QCCX ₂ SICSLX ₃ QLENYCN
<u>SEQ ID NO: 22</u> FVNQHLCGSHLVEALYLVCGERGFFYTX ₁ PTGEGPRRGIVE QCCX ₂ SICSLX ₃ QLENYCN
<u>SEQ ID NO: 23</u> FVNQHLCGSHLVEALYLVCGERGFFYTX ₁ PTEEGPRRGIVE QCCX ₂ SICSLX ₃ QLENYCN
<u>SEQ ID NO: 24</u> FVNQHLCGSHLVEALYLVCGERGFFYTX ₁ PTEEGPRRGIVE QCCX ₂ SICSX ₄ X ₃ QLENYCN
<u>SEQ ID NO: 25</u> FVNQHLCGSHLVEALYLVCGERGFFYTPX ₄ TEEGPRRGIVE QCCX ₂ SICSLX ₃ QLENYCN
<u>SEQ ID NO: 26</u> FVNQHLCGSHLVEALYLVCGERGFFYTPX ₄ TEEGPRRGIVE QCCX ₂ SICSLX ₃ QLENYCN
<u>SEQ ID NO: 27</u> FVNQHLCGSHLVEALYLVCGERGFFYTX ₄ PTEEGPRRGIVE QCCX ₂ SICSLX ₃ QLENYCN
<u>SEQ ID NO: 28 (<i>des</i>-B1-B3)</u> ---QHLCGSHLVEALYLVCGERGFFYTPX ₄ TEEGPRRGIVEQC CX ₂ SICSLX ₃ QLENYCN
<u>SEQ ID NO: 29</u> FVNQHLCGSHLVEALYLVCGERGFFYTX ₁ PTEEGPRRGIVE QCCX ₂ SICSLX ₃ QLENYCN

SEQ ID NO: 30

FVNQHLCGSHLVEALYLVCGERGFFYTX₁PTEEGRRGIVEQ
CCX₂SICSLX₃QLENYCN

SEQ ID NO: 31

FVNQHLCGSHLVEALYLVCGERGFFYTX₁PTEERRGIVEQC
CX₂SICSLX₃QLENYCN

SEQ ID NO: 32

FVNQHLCGSHLVEALYLVCGERGFFYTX₁PTEERGIVEQCC
X₂SICSLX₃QLENYCN

SEQ ID NO: 33

FVNQHLCGSHLVQALYLVCGERGFFYTPX₄TEEGPRRGIVE
QCCX₂SICSLX₃QLENYCN

SEQ ID NO: 34 (*des*-B1-B3)

---QHLCGSHLVEALYLVCGERGFFYTX₁PTEEGPRRGIVEQC
CX₂SICSLX₃QLENYCN

Where X₁ is chosen from the group Ala, Arg, Asn, Asp, Gln, Glu, or Lys; X₂ is chosen from the group Ala, Arg, Gln, Glu, or Lys; X₃ is chosen from the group Gln, Glu, Phe, Trp, or Tyr; and X₄ is chosen from the group Ala, Arg, Glu, Lys, or Pro.

Amino-acids sequence of single-chain insulin analogues of the present invention are also given in SEQ ID NO 35-49, corresponding to single-chain insulin analogs with optional elements at positions in the connecting domain as indicated by Y₁, Y₂, and so forth (magenta) and as including the above optional sequence features X₁, X₂, and so forth as indicated in green. As above, elements in red indicate sequences or substitutions that are otherwise not present in wild-type insulin or wild-type proinsulin. Dashes in SEQ ID NO 13 and 19 indicate deletion of N-terminal residues B1-B3 (designated *des*-B1-B3 analogues).

SEQ ID NO: 35

FVNQHLCGSHLVEALYLVCGERGFFYTX₁PTY₁SGPRRGIV
EQCCX₂SICSLX₃QLENYCN

SEQ ID NO: 36 FVNQHLCGSHLVEALYLVCGERGFFYTX₁PTS_{Y₂}GPRRGIV EQCCX₂SICSLX₃QLENYCN
SEQ ID NO: 37 FVNQHLCGSHLVEALYLVCGERGFFYTX₁PTY₁EGPRRGIV EQCCX₂SICSLX₃QLENYCN
SEQ ID NO: 38 FVNQHLCGSHLVEALYLVCGERGFFYTX₁PTY₁Y₂GPRRGIV EQCCX₂SICSLX₃QLENYCN
SEQ ID NO: 39 FVNQHLCGSHLVEALYLVCGERGFFYTX₁PTY₁Y₂GPRRGIV EQCCX₂SICSX₄X₃QLENYCN
SEQ ID NO: 40 FVNQHLCGSHLVEALYLVCGERGFFYTPX₁TY₁Y₂GPRRGIV EQCCX₂SICSLX₃QLENYCN
SEQ ID NO: 41 FVNQHLCGSHLVEALYLVCGERGFFYTPX₁TY₁Y₂GPRRGIV EQCCX₂SICSLX₃QLENYCN
SEQ ID NO: 42 FVNQHLCGSHLVEALYLVCGERGFFYTX₁PTY₁Y₂GPRRGIV EQCCX₂SICSLX₃QLENYCN
SEQ ID NO: 43 (<i>des</i>-B1-B3) ---QHLCGSHLVEALYLVCGERGFFYTPX₁TY₁Y₂GPRRGIVEQ CCX₂SICSLX₃QLENYCN
SEQ ID NO: 44 FVNQHLCGSHLVEALYLVCGERGFFYTX₁PTY₁Y₂GPRRGIV EQCCX₂SICSLX₃QLENYCN
SEQ ID NO: 45 FVNQHLCGSHLVEALYLVCGERGFFYTX₁PTY₁Y₂GRRGIVE QCCX₂SICSLX₃QLENYCN
SEQ ID NO: 46 FVNQHLCGSHLVEALYLVCGERGFFYTX₁PTY₁Y₂RRGIVEQ CCX₂SICSLX₃QLENYCN

SEQ ID NO: 47

FVNQHLCGSHLVEALYLVCGERGFFYTX₁PTY₁Y₂RGIVEQC
CX₂SICSLX₃QLENYCN

SEQ ID NO: 48

FVNQHLCGSHLVQALYLVCGERGFFYTPX₁TY₁Y₂GPRRGIV
EQCCX₂SICSLX₃QLENYCN

SEQ ID NO: 49 (*des*-B1-B3)

---QHLCGSHLVEALYLVCGERGFFYTX₁PTY₁Y₂GPRRGIVEQ
CCX₂SICSLX₃QLENYCN

Where X₁ is chosen from the group Ala, Arg, Asn, Asp, Gln, Glu, or Lys; X₂ is chosen from the group Ala, Arg, Gln, Glu, or Lys; X₃ is chosen from the group Gln, Glu, Phe, Trp, or Tyr; X₁ is chosen from the group Ala, Arg, Glu, Lys, or Pro; and where Y₁ and Y₂ are each either Asp or Glu.

Amino-acids sequence of single-chain insulin analogues of the present invention are also given in SEQ ID NO 50-64, corresponding to single-chain insulin analogs with additional 1-5 amino-acid residues (designated B₁₋₅ in blue below), with optional elements at positions in the connecting domain as indicated by Y₁, Y₂, and so forth (magenta) and as including the above optional sequence features X₁, X₂, and so forth as indicated in green. As above, elements in red indicate sequences or substitutions that are otherwise not present in wild-type insulin or wild-type proinsulin. Dashes in SEQ ID NO 13 and 19 indicate deletion of N-terminal residues B1-B3 (designated *des*-B1-B3 analogues).

SEQ ID NO: 50

FVNQHLCGSHLVEALYLVCGERGFFYTX₁PTY₁SGPB₁₋₅RRG
IVEQCCX₂SICSLX₃QLENYCN

SEQ ID NO: 51

FVNQHLCGSHLVEALYLVCGERGFFYTX₁PTS_{Y₂}GPB₁₋₅RRG
IVEQCCX₂SICSLX₃QLENYCN

<u>SEQ ID NO: 52</u> FVNQHLCGSHLVEALYLVCGERGFFYTX ₁ PTY ₁ EGPB ₁₋₅ RRG IVEQCCX ₂ SICSLX ₃ QLENYCN
<u>SEQ ID NO: 53</u> FVNQHLCGSHLVEALYLVCGERGFFYTX ₁ PTY ₁ Y ₂ GPB ₁₋₅ RRG IVEQCCX ₂ SICSLX ₃ QLENYCN
<u>SEQ ID NO: 54</u> FVNQHLCGSHLVEALYLVCGERGFFYTX ₁ PTY ₁ Y ₂ GPB ₁₋₅ RRG IVEQCCX ₂ SICSX ₄ X ₃ QLENYCN
<u>SEQ ID NO: 55</u> FVNQHLCGSHLVEALYLVCGERGFFYTPX ₁ TY ₁ Y ₂ GPB ₁₋₅ RRG IVEQCCX ₂ SICSLX ₃ QLENYCN
<u>SEQ ID NO: 56</u> FVNQHLCGSHLVEALYLVCGERGFFYTPX ₁ TY ₁ Y ₂ GPB ₁₋₅ RRG IVEQCCX ₂ SICSLX ₃ QLENYCN
<u>SEQ ID NO: 57</u> FVNQHLCGSHLVEALYLVCGERGFFYTX ₁ PTY ₁ Y ₂ GPB ₁₋₅ RRG IVEQCCX ₂ SICSLX ₃ QLENYCN
<u>SEQ ID NO: 58 (des-B1-B3)</u> ---QHLCGSHLVEALYLVCGERGFFYTPX ₁ TY ₁ Y ₂ GPB ₁₋₅ RRGIV EQCCX ₂ SICSLX ₃ QLENYCN
<u>SEQ ID NO: 59</u> FVNQHLCGSHLVEALYLVCGERGFFYTX ₁ PTY ₁ Y ₂ GPB ₁₋₅ RRG IVEQCCX ₂ SICSLX ₃ QLENYCN
<u>SEQ ID NO: 60</u> FVNQHLCGSHLVEALYLVCGERGFFYTX ₁ PTY ₁ Y ₂ GB ₁₋₅ RRGI VEQCCX ₂ SICSLX ₃ QLENYCN
<u>SEQ ID NO: 61</u> FVNQHLCGSHLVEALYLVCGERGFFYTX ₁ PTY ₁ Y ₂ B ₁₋₅ RRGIV EQCCX ₂ SICSLX ₃ QLENYCN
<u>SEQ ID NO: 62</u> FVNQHLCGSHLVEALYLVCGERGFFYTX ₁ PTY ₁ Y ₂ B ₁₋₅ RGIVE QCCX ₂ SICSLX ₃ QLENYCN

SEQ ID NO: 63

FVNQHLCGSHLVQALYLVCGERGFFYTPX₁TY₁Y₂GPB₁₋₅RR
GIVEQCCX₂SICSLX₃QLENYCN

SEQ ID NO: 64 (des-B1-B3)

---QHLCGSHLVEALYLVCGERGFFYTX₁PTY₁Y₂GPB₁₋₅RRGIV
EQCCX₂SICSLX₃QLENYCN

Where X₁ is chosen from the group Ala, Arg, Asn, Asp, Gln, Glu, or Lys; X₂ is chosen from the group Ala, Arg, Gln, Glu, or Lys; X₃ is chosen from the group Gln, Glu, Phe, Trp, or Tyr; X₁ is chosen from the group Ala, Arg, Glu, Lys, or Pro; where Y₁ and Y₂ are each either Asp or Glu; and where residues B₁, B₂, B₃, B₄, B₅, are each optionally present and may be drawn from the group Ala, Asn, Gln, Gly, Pro, Ser or Thr.

The following DNA sequence encodes single-chain insulin analogue specified in SEQ ID NO 6 (see above) with codons optimized for usage patterns in *Pichia pastoris*.

SEQ. ID. NO 65

TTCGTCAATCAACACTTGTGTGGTTCCCACTTGGTTGAGGCATTGTACTTG
GTCTGTGGTGAGAGAGGATTCTTCTACACCGATCCAACCTGGTGGTGGTCCT
AGAAGAGGAATCGTCGAGCAATGTTGCCACTCCATTTGTTTCCTTGGAACA
ATTGGAAAACACTACTGCAACTAA

The following DNA sequence encodes single-chain insulin analogue specified in SEQ ID NO 7 (see above) with codons optimized for usage patterns in *Pichia pastoris*.

SEQ. ID. NO 66

TTCGTCAATCAACACTTGTGTGGTTCCCACTTGGTTGAGGCATTGTACTTG
GTCTGTGGTGAGAGAGGATTCTTCTACACCGATCCAACCTGGTGAGGGTCC
TAGAAGAGGAATCGTCGAGCAATGTTGCCACTCCATTTGTTTCCTTGGAAC
AATTGGAAAACACTACTGCAACTAA

The following DNA sequence encodes single-chain insulin analogue specified in SEQ ID NO 8 (see above) with codons optimized for usage patterns in *Pichia pastoris*.

SEQ. ID. NO 67

TTCGTCAATCAGCACTTGTGTGGTTCCCACTTGGTTGAGGCTTTGTACTTG
 GTTTGTGGTGAGAGAGGTTTCTTCTACACTGATCCAACCTGAAGAGGGTCC
 AAGAAGAGGTATCGTTGAGCAGTGTTGTCACCTCCATCTGTTTCCTTGGAGCA
 GTTGGAGAACTACTGTAACCTGA

The following DNA sequence encodes single-chain insulin analogue specified in SEQ ID NO 9 (see above) with codons optimized for usage patterns in *Pichia pastoris*.

SEQ. ID. NO 68

TTCGTCAATCAGCACTTGTGTGGTTCCCACTTGGTTGAGGCTTTGTACTTG
 GTTTGTGGTGAGAGAGGTTTCTTCTACACTGATCCAACCTGAAGAGGGTCC
 AAGAAGAGGTATCGTTGAGCAGTGTTGTCACCTCCATCTGTTTCCTGGGAGC
 AGTTGGAGAACTACTGTAACCTGA

The following DNA sequence encodes single-chain insulin analogue specified in SEQ ID NO 10 (see above) with codons optimized for usage patterns in *Pichia pastoris*.

SEQ. ID. NO 69

TTCGTCAATCAGCACTTGTGTGGTTCCCACTTGGTTGAGGCTTTGTACTTG
 GTTTGTGGTGAGAGAGGTTTCTTCTACACTCCAGAACTGAAGAGGGTCC
 AAGAAGAGGTATCGTTGAGCAGTGTTGTCACCTCCATCTGTTTCCTTGGAGCA
 GTTGGAGAACTACTGTAACCTGA

The following DNA sequence encodes single-chain insulin analogue specified in SEQ ID NO 11 (see above) with codons optimized for usage patterns in *Pichia pastoris*.

SEQ. ID. NO 70

TTCGTCAATCAGCACTTGTGTGGTTCCCACTTGGTTGAGGCTTTGTACTTG
 GTTTGTGGTGAGAGAGGTTTCTTCTACACTCCAAGAACTGAAGAGGGTCC
 AAGAAGAGGTATCGTTGAGCAGTGTTGTCACCTCCATCTGTTTCCTTGGAGCA
 GTTGGAGAACTACTGTAACCTGA

The following DNA sequence encodes single-chain insulin analogue specified in SEQ ID NO 12 (see above) with codons optimized for usage patterns in *Pichia pastoris*.

SEQ. ID. NO 71

TTCGTCAATCAGCACTTGTGTGGTTCCCACTTGGTTGAGGCTTTGTACTTG
 GTTTGTGGTGAGAGAGGTTTCTTCTACACTGAGCCAACCTGAAGAGGGTCC
 AAGAAGAGGTATCGTTGAGCAGTGTTGTCACTCCATCTGTTTCCTTGGAGCA
 GTTGGAGAACTACTGTAACCTGA

The following DNA sequence encodes single-chain insulin analogue specified in SEQ ID NO 13 (see above) with codons optimized for usage patterns in *Pichia pastoris*.

SEQ. ID. NO 72

TTCGTCAAACAGCACTTGTGTGGTTCCCACTTGGTTGAGGCTTTGTACTTG
 GTTTGTGGTGAGAGAGGTTTCTTCTACACTCCAGAACTGAAGAGGGTCC
 AAGAAGAGGTATCGTTGAGCAGTGTTGTCACTCCATCTGTTTCCTTGGAGCA
 GTTGGAGAACTACTGTAACCTGA

The following DNA sequence encodes single-chain insulin analogue specified in SEQ ID NO 15 (see above) with codons optimized for usage patterns in *Pichia pastoris*.

SEQ. ID. NO 73

TTCGTTAACCAGCACTTGTGTGGTTCCCACTTGGTTGAGGCTTTGTACTTG
 GTTTGTGGTGAGAGAGGTTTCTTCTACACTGATCCAACCTGAAGAGAGAAG
 AGGTATCGTTGAGCAGTGTTGTCACTCCATCTGTTTCCTTGGAGCAGTTGGA
 GAACTACTGTAACCTAA

The following DNA sequence encodes single-chain insulin analogue specified in SEQ ID NO 16 (see above) with codons optimized for usage patterns in *Pichia pastoris*.

SEQ. ID. NO 74

TTCGTTAACCAGCACTTGTGTGGTTCCCACTTGGTTGAGGCTTTGTACTTG
 GTTTGTGGTGAGAGAGGTTTCTTCTACACTGATCCAACCTGAAGAGAGAAG
 AGGTATCGTTGAGCAGTGTTGTCACTCCATCTGTTTCCTTGGAGCAGTTGGA
 GAACTACTGTAACCTAA

The following DNA sequence encodes single-chain insulin analogue specified in SEQ ID NO 17 (see above) with codons optimized for usage patterns in *Pichia pastoris*.

SEQ. ID. NO 75

TTCGTTAACCAGCACTTGTGTGGTTCCCACTTGGTTGAGGCTTTGTACTTG
 GTTTGTGGTGAGAGAGGTTTCTTCTACACTGATCCAACCTGAAGAGAGAGG
 TATCGTTGAGCAGTGTTGTCACCTCCATCTGTTCCCTTGGAGCAGTTGGAGAA
 CTACTGTAACCTAA

The following DNA sequence encodes single-chain insulin analogue specified in SEQ ID NO 18 (see above) with codons optimized for usage patterns in *Pichia pastoris*.

SEQ. ID. NO 76

TTCGTCAATCAGCACTTGTGTGGTTCCCACTTGGTTCAGGCTTTGTACTTG
 GTTTGTGGTGAGAGAGGTTTCTTCTACACTCCAGAACTGAAGAGGGTCC
 AAGAAGAGGTATCGTTGAGCAGTGTTGTCACCTCCATCTGTTCCCTTGGAGCA
 GTTGGAGAACTACTGTAACCTGA

The following DNA sequence encodes single-chain insulin analogue specified in SEQ ID NO 19 (see above) with codons optimized for usage patterns in *Pichia pastoris*.

SEQ. ID. NO 77

TTCGTCAAACAGCACTTGTGTGGTTCCCACTTGGTTGAGGCTTTGTACTTG
 GTTTGTGGTGAGAGAGGTTTCTTCTACACTGACCCAACCTGAAGAGGGTCC
 AAGAAGAGGTATCGTTGAGCAGTGTTGTCACCTCCATCTGTTCCCTTGGAGCA
 GTTGGAGAACTACTGTAACCTGA

Analogous synthetic genes have been prepared and cloned in *Pichia pastoris* encoding SCI-59A (see below) and derivatives of SCI-59A and SCI-59B containing the additional substitution Glu^{B13}→Gln as embodied in SEQ. ID NO 31-37.

Two single-chain insulin analogues of the present invention (encoded by SEQ ID NO 8 and SEQ ID NO 10; respectively designated SCI-57DP and SCI-57PE) were prepared by biosynthesis of a precursor polypeptide in *Pichia pastoris*; this system secretes a folded protein containing native disulfide bridges with cleavage N-terminal extension peptide. Efficiency of over-expression (> 200 mg/l culture in fermentation) is illustrated in Figure 5. The cleaved single-chain insulin products had length 57, the

sum of a 30-residue B-domain, 6-residue C-domain (sequence EEGPRR in each case), and 21-residue A-domain. The formal isoelectric points (pI) of SCI-57DP and SCI-57PE were in each case predicted to be shifted below 5.0 by the removal of a positive charge at wild-type position B29 (LysB29), by acidic substitutions at B28 or B29, by an acidic substitution at A14 (TyrA14→Glu), and by offsetting basic and acidic side chains in the C-domain.

The thermodynamic stabilities of the single-chain analogues were probed by CD-monitored guanidine denaturation as described (Hua, Q.X., et al. *J. Biol. Chem.* 283, 14703-16 (2008)). The results (column 2 of Table 1) indicate that SCI-57DP and SCI-57PE are each more stable to chemical denaturation than are wild-type insulin or KP-insulin. In each case higher concentrations of guanidine-HCl were required to achieve 50% unfolding of the protein (column 3 in Table 1); a trend is observed toward larger values of *m* (column 4), suggesting more efficient desolvation of nonpolar surfaces in the folded state. The susceptibility of SCI-57PE to fibrillation on gentle agitation at 37 °C was found to be markedly prolonged relative to wild-type insulin or KP-insulin (column 5 of Table 1). Whereas wild-type insulin and KP-insulin form fibrils in less than 10 days under these conditions, SCI-57PE is refractory to fibrillation for at least 9 months.

The receptor-binding affinities of SCI-57DP and SCI-57PE were determined in relation to wild-type human insulin. The assay employed the A isoform of the insulin receptor. Relative to human insulin (equilibrium dissociation constant 0.05(±0.01) nM), SCI-57DP and SCI-57PE exhibited respective binding constants of 0.06(±0.01) nM and 0.08(±0.01) nM. The affinity of SCI-57DP for the mitogenic Type 1 IGF-I receptor was at least fivefold lower than that of wild-type human insulin. The protocol for assay of receptor-binding activities was as follows. Microtiter strip plates (Nunc Maxisorb) were incubated overnight at 4° C with AU5 IgG (100 µl/well of 40 mg/ml in phosphate-buffered saline). Binding data were analyzed by a two-site sequential model. Data were corrected for nonspecific binding (amount of radioactivity remaining membrane associated in the presence of 1 µM human insulin. In all assays the percentage of tracer bound in the absence of

competing ligand was less than 15% to avoid ligand-depletion artifacts. Dissociation constants (K_d) were determined by fitting to a mathematic model as described by Whittaker and Whittaker (2005. *J. Biol. Chem.* 280: 20932-20936); the model employed non-linear regression with the assumption of heterologous competition (Wang, 1995, *FEBS Lett.* 360: 111-114).

Table 1. Thermodynamic and Physical Stabilities Insulin Analogues at 25 °C^a

analog	ΔG_u^b kcal/mol	C_{mid} (M) ^c	m (kcal/mol/M) ^d	fib. lag time ^e
WT insulin	3.6 ± 0.1	4.9 ± 0.07	0.73 ± 0.01	3-6 days
KP-insulin	3.1 ± 0.1	4.5 ± 0.1	0.69 ± 0.01	2-4 days
SCI-57DP	4.3 ± 0.1	5.7 ± 0.13	0.74 ± 0.02	ND ^f
SCI-57PE	4.6 ± 0.1	5.7 ± 0.11	0.80 ± 0.02	>9 mo

^aThermodynamic stabilities were inferred from CD-detected guanidine denaturation (222 nm) at 25 °C analyzed by a two-state model extrapolated to zero denaturant concentration.

^b ΔG_u represents the apparent change in free energy on denaturation in guanidine-HCl as extrapolated to zero denaturant concentration by a two-state model.

^c C_{mid} is defined as that concentration of guanidine-HCl at which 50% of the protein is unfolded.

^dThe m value is the slope of unfolding free energy ΔG_u versus molar concentration of denaturant; it correlates with the extent of exposure of nonpolar surfaces on denaturation.

^eFibrillation lag time was measure in days prior to onset of thioflavin-T-positive aggregation; analogues in triplicate were gently rocked at 45°C in Tris-HCl formulation at a nominal strength of U-100.

^fND; not determined

Biological activity and pharmacodynamics were tested in male Sprague-Dawley rats (*ca.* 300 g) rendered diabetic by streptozotocin (Fig. 6). PD effects of s.q. injection of U-100 (0.6 mM) SCI-57PE and SCI-57DP were evaluated in relation to Humalog® and the 25-75 Humalog® pre-mix; the resulting overall profile of the blood-glucose concentration (Fig. 6A) indicated that the PD properties of our two candidates are similar to the pre-mixed Lilly product, recapitulating both its long-acting (120-540 min) and rapid-acting components (Fig. 6B). Initial rates of decline of the blood glucose concentration over the first hour post-injection are shown in Fig. 7.

Thermal stability of SCIs. Retention or loss of potency of SCI-57DP was

evaluated in the above rats under conditions favoring rapid degradation of current insulin products (*i.e.*, gentle agitation at 45 °C in a glass vial in the presence of an air-liquid interface; Fig. 8). Fresh materials were employed in Figure 8A. Controls were provided by Humalog® and Lantus®. Whereas Lantus® was inactive after 11 days (○ in Fig. 8B) and Humalog® within 5 days (not shown), SCI-2 (◆ and □) maintained full activity when tested as a clear solution after 57 days (Fig. 8B). SCI-57PE (whose G_u is greater than that of SCI-DP; Table 1 above), exhibits similar resistance to degradation (not shown).

Structural studies employed circular dichroism (CD) and NMR spectroscopy. The far-ultraviolet CD spectra of SCI-57DP and SCI-57PE indicated a predominance of alpha-helix in accordance with the native structure of human insulin and with the solution structure of a single-chain insulin analogue (Hua, Q.X., et al. *J. Biol. Chem.* 283, 14703-16 (2008)). The NMR studies focused on SCI-57DP in aqueous solution (pH 7-8) in the absence of zinc ions in light of its monomeric status at protein concentrations < 1 mM. Spectra were acquired at a proton frequency of 700 MHz. The 2D-NMR NOESY spectrum and ^1H - ^{15}N heteronuclear single-quantum coherence (HSQC) 2D “fingerprint” spectrum provided evidence for a folded structure; patterns of NOEs and chemical shifts are in accord with prior analysis of a 57-residue single-chain insulin analogue (Hua, Q.X., et al. *J. Biol. Chem.* 283, 14703-16 (2008)).

Speed of hexamer disassembly was evaluated in R_6 cobalt hexamers of SCI-1 at 25 °C and pH 7.4 by visible absorption spectroscopy. This assay exploits the blue d-d absorption band of the two tetrahedral Co^{2+} sites in the R_6 insulin hexamer to monitor the rate of metal-ion release and sequestration by excess chelator EDTA; the octahedral Co^{2+} -EDTA complex is colorless. Remarkably, whereas the Lilly Co^{2+} -EDTA sequestration assay of wild-type insulin leads under these conditions to a *mono-exponential* loss of absorbance at 574 nm (black line in Fig. 9), SCI-1 exhibits a *bi-exponential* transition with fast phase (more rapid than insulin *lispro*; not shown) and a slow phase (slower than wild-type insulin; green line in Fig. 9). Among the portfolio of two-chain insulin analogs tested by the Weiss group at CWRU, such biphasic kinetic behavior in the EDTA assay is unprecedented. This assay correlated

with PK studies in animals (and subsequently in humans), these spectroscopic results motivated our overarching hypothesis that the present SCIs would exhibit biphasic PK properties in a subcutaneous depot (as in rats). The molecular mechanism of this biphasic behavior remains to be determined but may involve the phenol-dependent RT transition as found in insulin *degludec* (a new basal analog from Novo-Nordisk).

A method for treating a patient with diabetes mellitus comprises administering a single-chain insulin analogue as described herein. It is another aspect of the present invention that the single-chain insulin analogues may be prepared either in yeast (*Pichia pastoris*) or subject to total chemical synthesis by native fragment ligation. The synthetic route of preparation is preferred in the case of non-standard modifications, such as D-amino-acid substitutions, halogen substitutions within the aromatic rings of Phe or Tyr, or O-linked modifications of Serine or Threonine by carbohydrates; however, it would be feasible to manufacture a subset of the single-chain analogues containing non-standard modifications by means of extended genetic-code technology or four-base codon technology (for review, see Holsaka, T., & Sisido, M., 2012). It is yet another aspect of the present invention that use of non-standard amino-acid substitutions can augment the resistance of the single-chain insulin analogue to chemical degradation or to physical degradation. We further envision the analogues of the present invention providing a method for the treatment of diabetes mellitus or the metabolic syndrome. The route of delivery of the insulin analogue is by subcutaneous injection through the use of a syringe or pen device.

A single-chain insulin analogue of the present invention may also contain other modifications, such as a halogen atom at positions B24, B25, or B26 as described more fully in co-pending U.S. Patent Application No. 13/018,011, the disclosure of which is incorporated by reference herein. An insulin analogue of the present invention may also contain a foreshortened B-chain due to deletion of residues B1-B3 as described more fully in co-pending U.S. Provisional Patent Application 61/589,012.

A pharmaceutical composition may comprise such insulin analogues and which may optionally include zinc. Zinc ions may be included at varying zinc

ion:protein ratios, ranging from 2.2 zinc atoms per insulin analogue hexamer to 10 zinc atoms per insulin analogue hexamer. The pH of the formulation is in the range pH 7.0-8.0; a buffer (typically sodium phosphate or Tris-hydrochloride) may or may not be present. In such a formulation, the concentration of the insulin analogue would typically be between about 0.6-5.0 mM; concentrations up to 5 mM may be used in vial or pen; the more concentrated formulations (U-200 or higher) may be of particular benefit in patients with marked insulin resistance. Excipients may include glycerol, glycine, arginine, Tris, other buffers and salts, and anti-microbial preservatives such as phenol and *meta*-cresol; the latter preservatives are known to enhance the stability of the insulin hexamer. Such a pharmaceutical composition may be used to treat a patient having diabetes mellitus or other medical condition by administering a physiologically effective amount of the composition to the patient.

Based upon the foregoing disclosure, it should now be apparent that the single-chain insulin analogues provided will carry out the objects set forth hereinabove. Namely, these insulin analogues exhibit enhanced resistance to fibrillation while retaining desirable pharmacokinetic and pharmacodynamic features (conferring biphasic action) and maintaining at least a fraction of the biological activity of wild-type insulin. It is, therefore, to be understood that any variations evident fall within the scope of the claimed invention and thus, the selection of specific component elements can be determined without departing from the spirit of the invention herein disclosed and described.

The following literature is cited to demonstrate that the testing and assay methods described herein would be understood by one of ordinary skill in the art.

Brange J, editor. (1987) *Galenics of Insulin: The Physico-chemical and Pharmaceutical Aspects of Insulin and Insulin Preparations*. Berlin: Springer Berlin Heidelberg.

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- Rolla, A.R., and Rakel, R.E. (2005) Practical approaches to insulin therapy for type 2 diabetes mellitus with premixed insulin analogues. *Clin. Ther.* **27**, 1113-25.

- Wang, Z.X. (1995) An exact mathematical expression for describing competitive binding of two different ligands to a protein molecule *FEBS Lett.* **360**: 111-114.
- Whittaker, J., and Whittaker, L. (2005) Characterization of the functional insulin binding epitopes of the full-length insulin receptor. *J. Biol. Chem.* **280**: 20932-20936.

CLAIMS

What is claimed is:

1. A single-chain insulin comprising:
 - a C-domain of from 6 to 11 amino acid residues comprising at least two acidic residues at the N-terminal side of the C-domain and at least two basic residues at the C-terminal side of the C-domain peptide;
 - a basic amino acid residue at the position corresponding to A8 of human insulin, and
 - an acidic amino acid residue at the position corresponding to A14 of human insulin.
2. The single-chain insulin of claim 1, wherein the C-domain has the amino acids Glu-Glu at the N-terminal side of the C-domain.
3. The single-chain insulin of claim 1 or 2, wherein the C-domain has the amino acids Arg-Arg, Lys-Lys, Arg-Lys, or Lys-Arg at the C-terminal side of the C-domain.
4. The single-chain insulin of any one of claims 1 to 3, wherein the C-domain contains a 2 to 4 amino acid joint region between the acidic residues and the basic residues.
5. The single-chain insulin of claim 4, wherein the joint region consists essentially of one or more of glycine, serine, and proline residues.
6. The single-chain insulin of claim 5, wherein the joint region comprises or consists of Gly-Pro.
7. The single-chain insulin of any one of claims 1 to 6, wherein the amino acid at the position corresponding to A8 is Lys, Arg, Hist, or Orn.

8. The single-chain insulin of claim 7, wherein the amino acid at the position corresponding to A8 is Lys or Arg.
9. The single-chain insulin of any one of claims 1 to 8, wherein the amino acid at the position corresponding to A14 is Glu.
10. The single-chain insulin of any one of claims 1 to 9, wherein the single chain insulin comprises an amino acid substitution at the position corresponding to B28 and/or B29.
11. The single-chain insulin of claim 10, wherein the substitution at the position corresponding to B28 and/or B29 is an acidic amino acid.
12. The single-chain insulin of any one of claims 1 to 11, having a Histidine substitution at the position corresponding to B10 of human insulin.
13. The single-chain insulin of any one of claims 1 to 12, wherein the single chain insulin has a substitution of Gly, Ala, or Ser for Asn at position A21.
14. The single-chain insulin of any one of claims 1 to 13, wherein the single chain insulin has the amino acid sequence of any one of SEQ ID NOS: 6-64.
15. The single-chain insulin of any one of claims 1 to 14, wherein the single chain insulin has a predicted isoelectric point below 5.0.
16. A pharmaceutical composition comprising the single-chain insulin of any one of claims 1 to 15, formulated at a pH within the range 7.0 to 8.0.
17. The pharmaceutical composition of claim 16, further comprising a pH buffer.

18. The pharmaceutical composition of claim 16 or 17, wherein the single-chain insulin is formulated at a concentration of 0.6 mM to 5.0 mM.
19. The pharmaceutical composition of claim 16 or 17, wherein the single-chain insulin is formulated at a strength of U-100, U-200, U-300, U-400, or U-500.
20. The pharmaceutical composition of claim 16 or 17, wherein the single-chain insulin is formulated at a strength of between U-500 and U-1000.
21. The pharmaceutical composition of any one of claims 16 to 20, further comprising 2 to 4 zinc ions per insulin hexamer.
22. The pharmaceutical composition of any one of claims 16 to 20, further comprising less than 2 zinc ions per insulin hexamer.
23. A method for treating diabetes mellitus comprising, subcutaneously administering the pharmaceutical composition of any one of claims 16 to 22 to a patient in need thereof.
24. The method of claim 23, wherein the pharmaceutical composition is administered twice daily.

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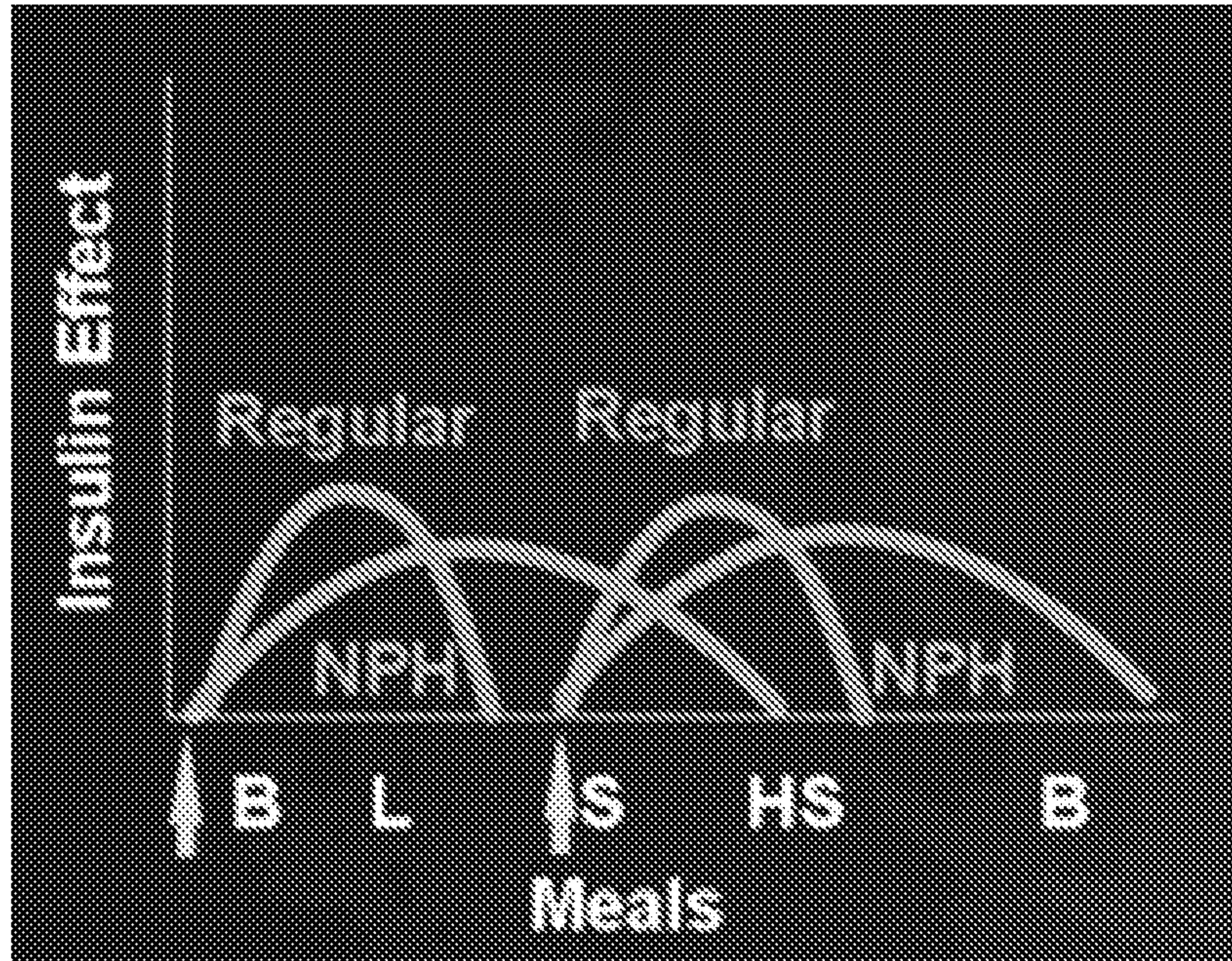


FIGURE 1

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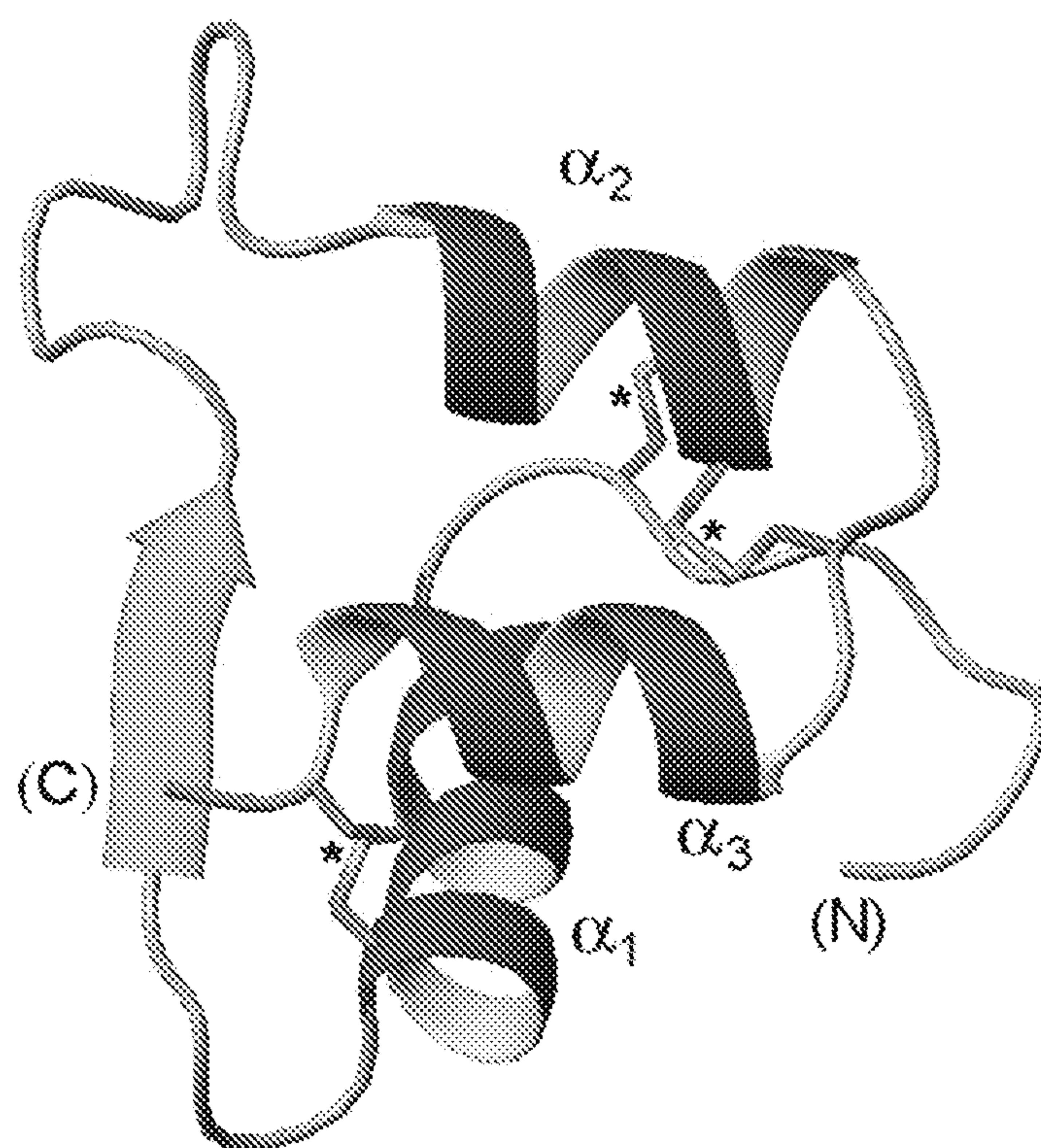


FIGURE 2

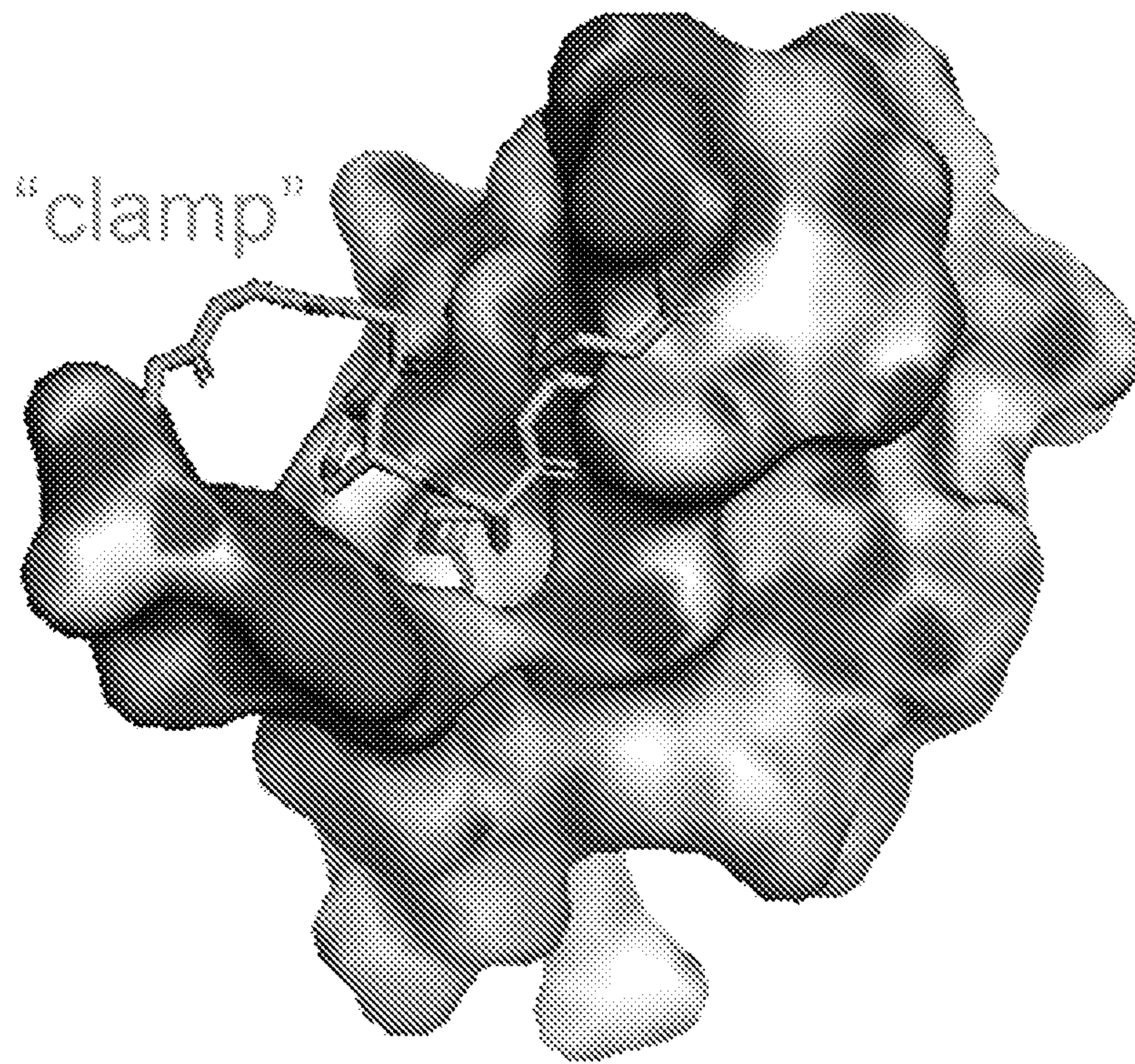


FIGURE 3

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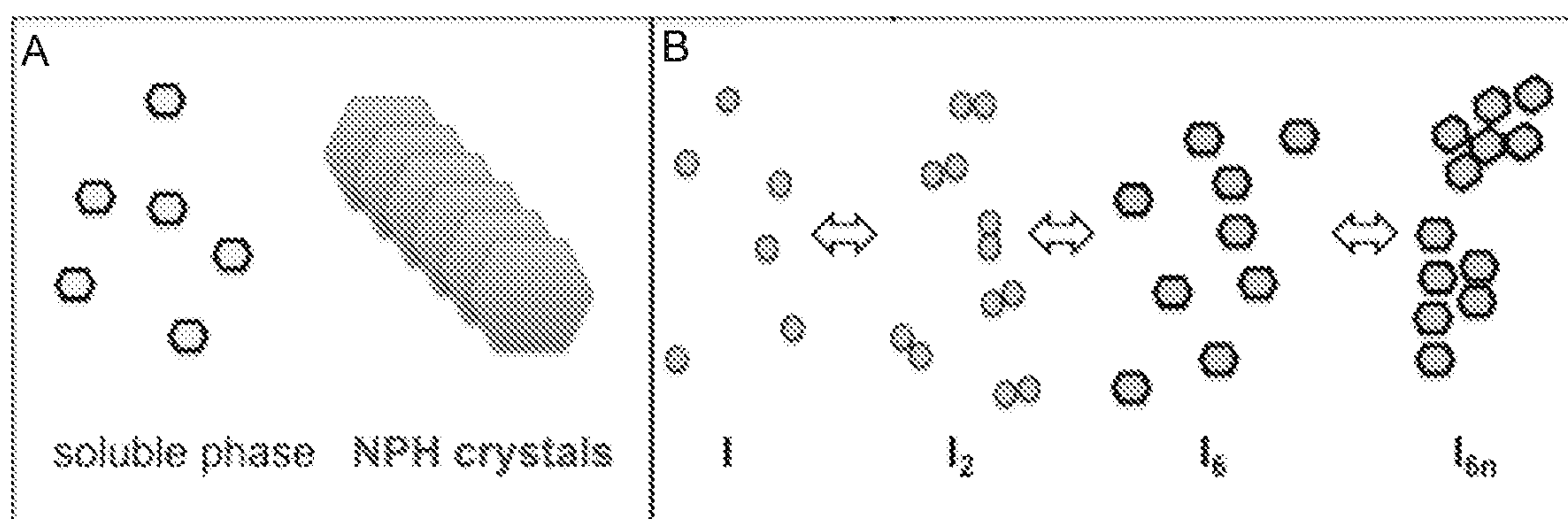


FIGURE 4

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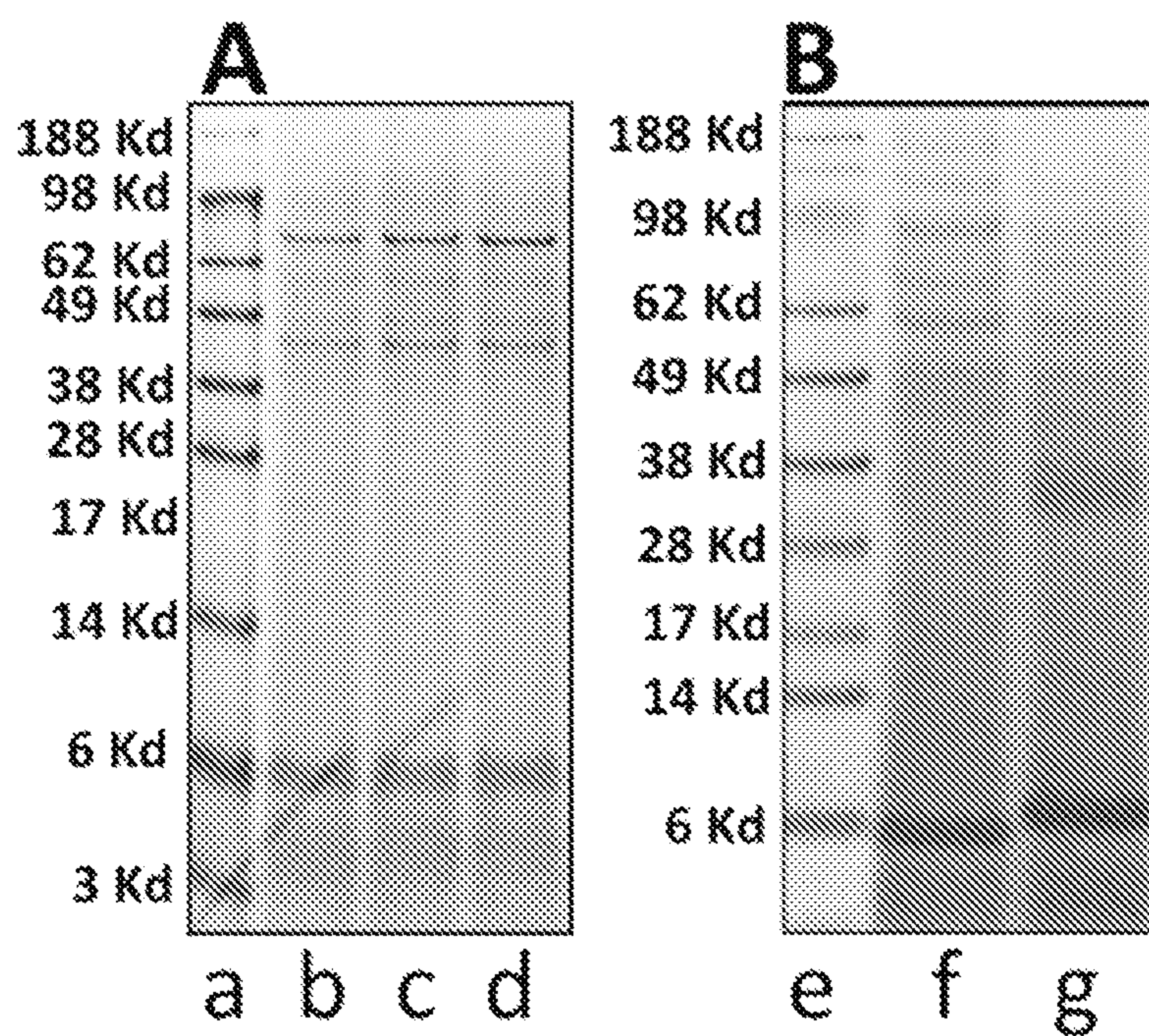


FIGURE 5

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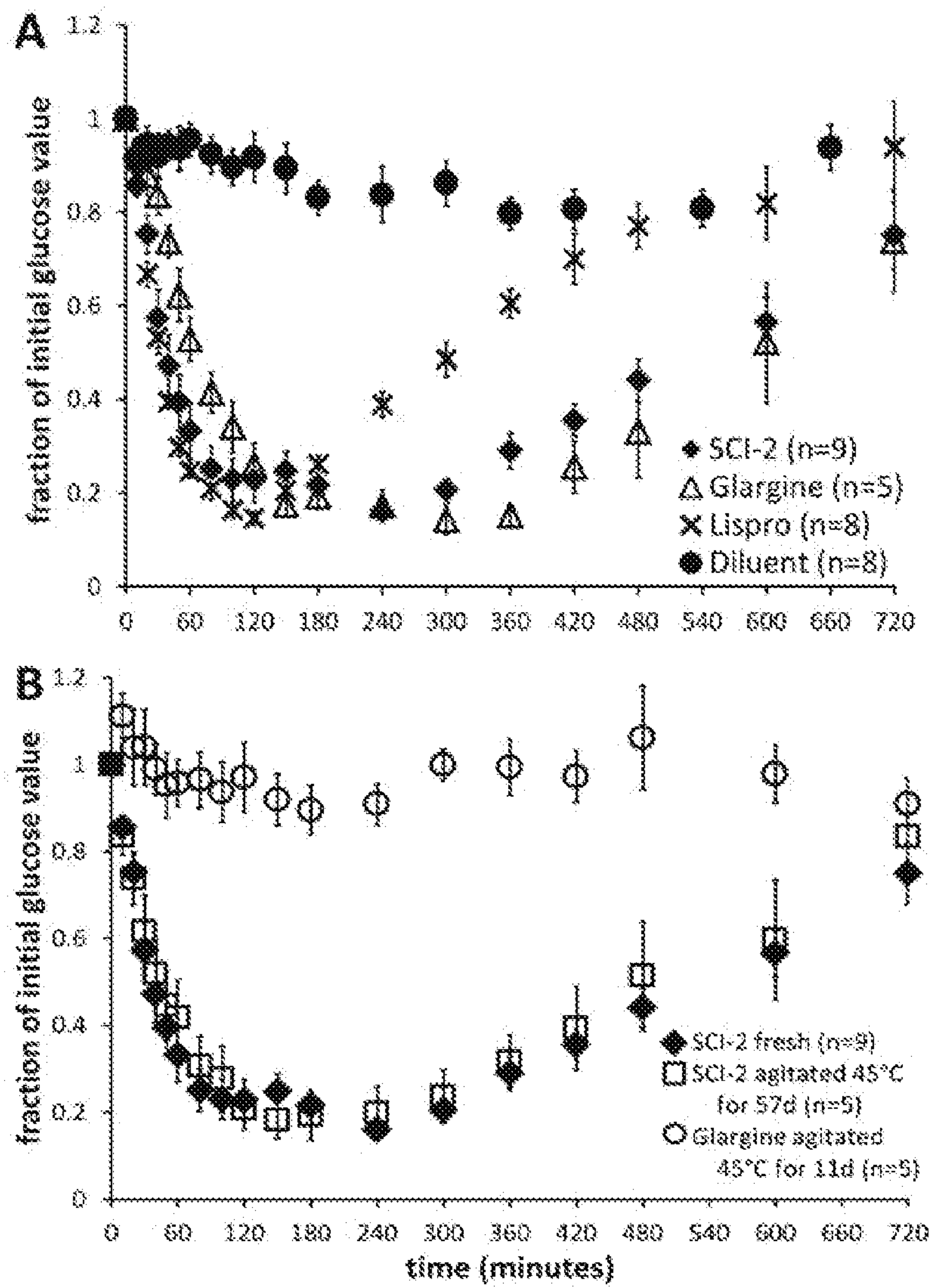


FIGURE 6

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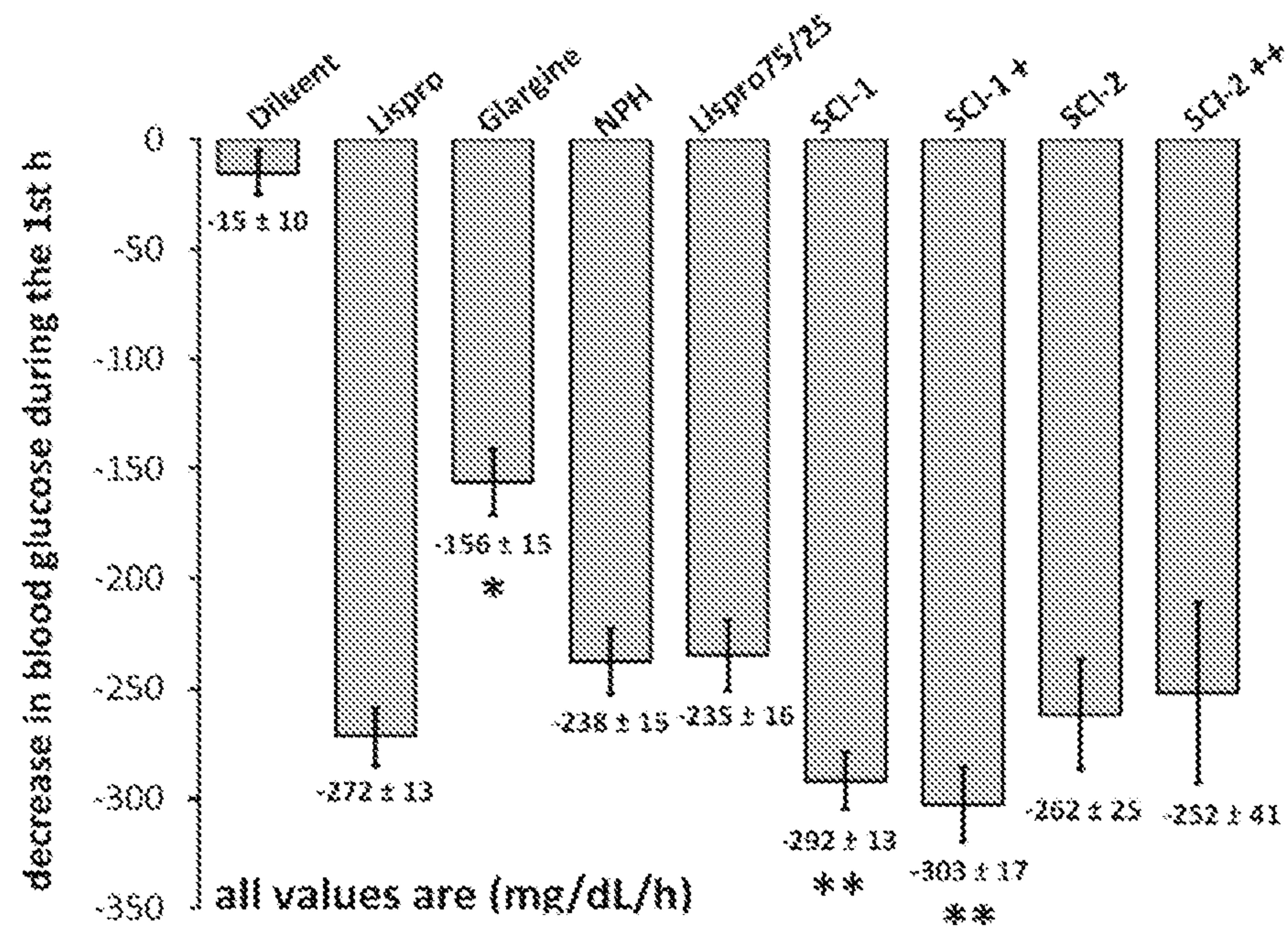


FIGURE 7

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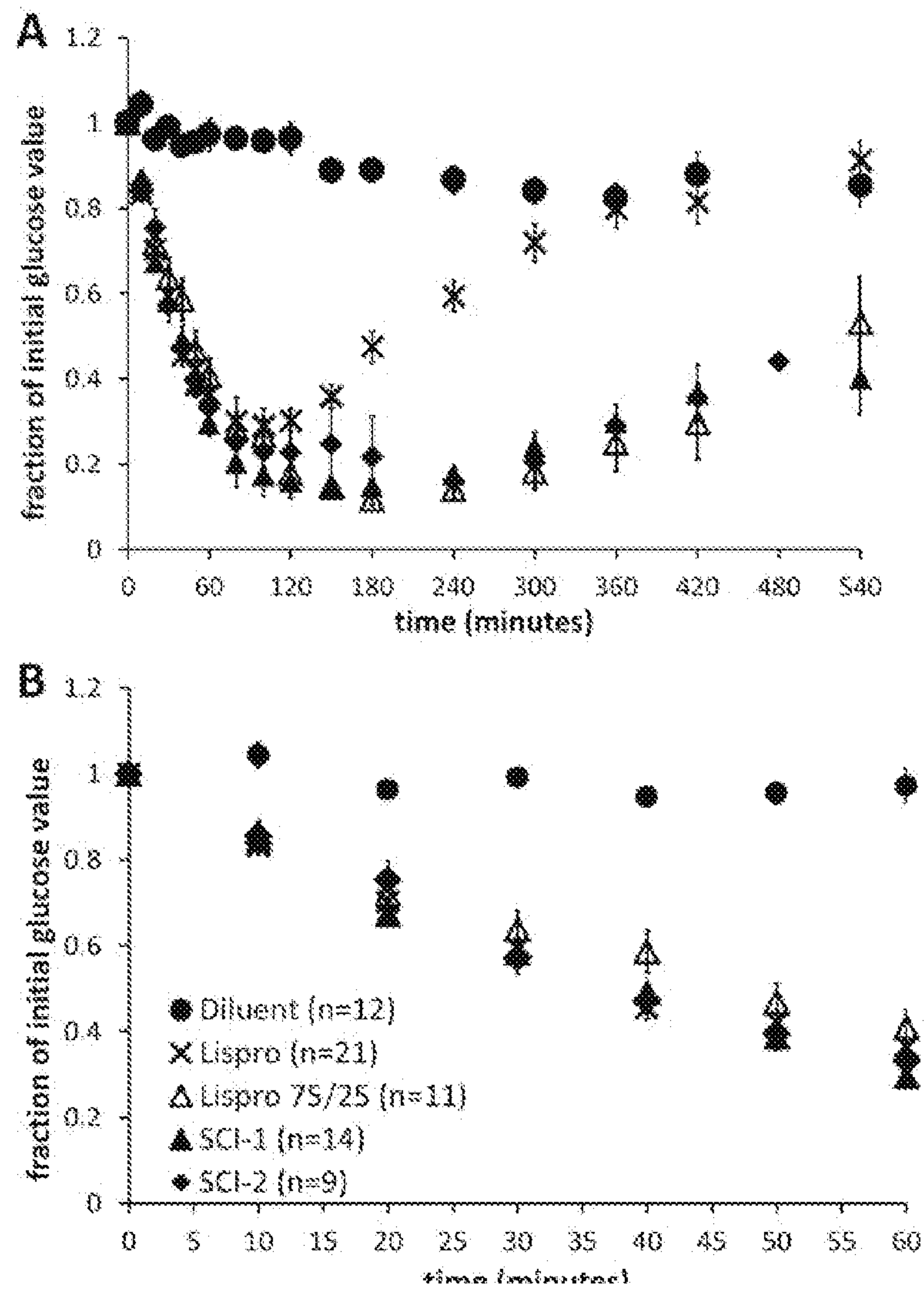


FIGURE 8

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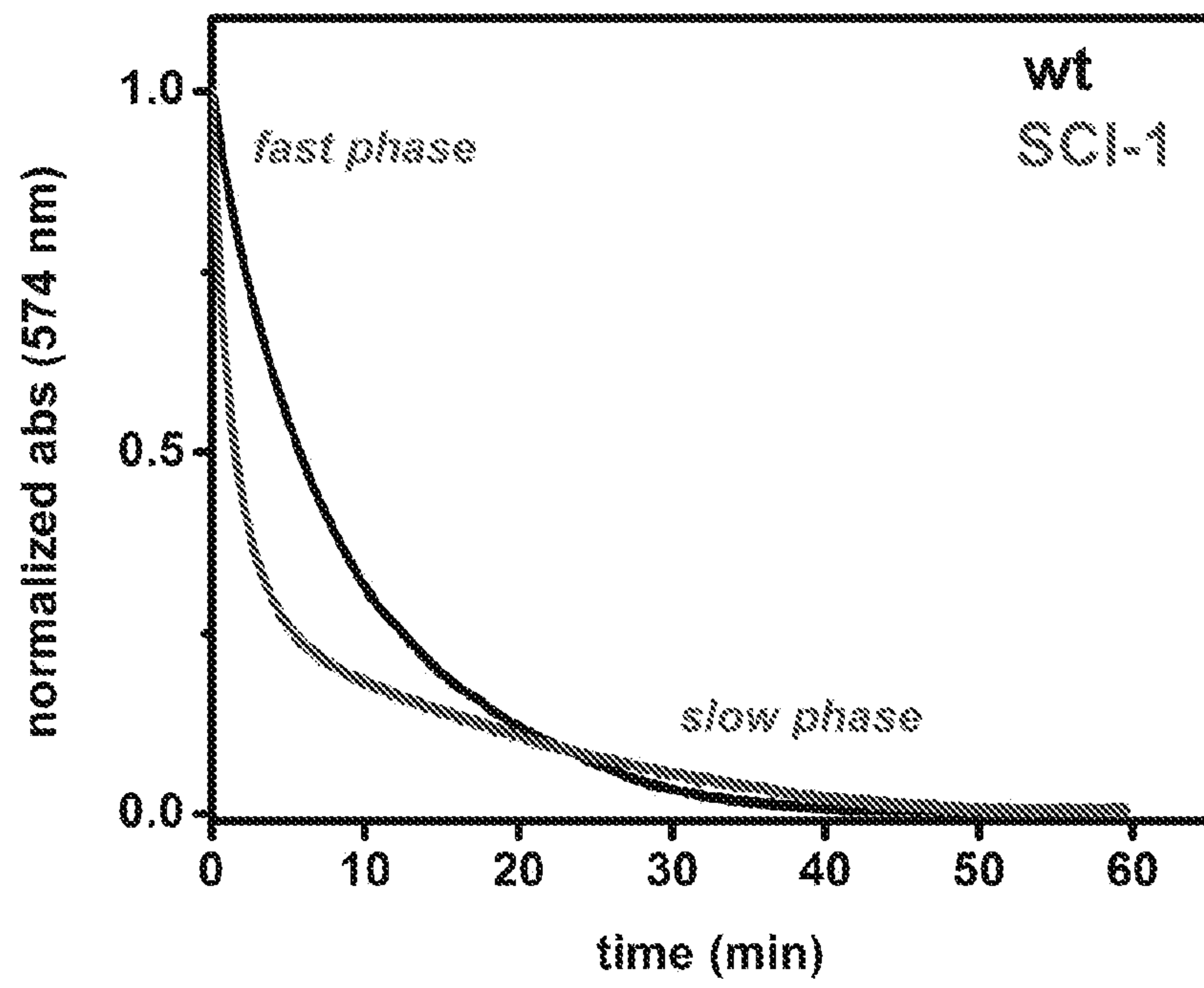


FIGURE 9

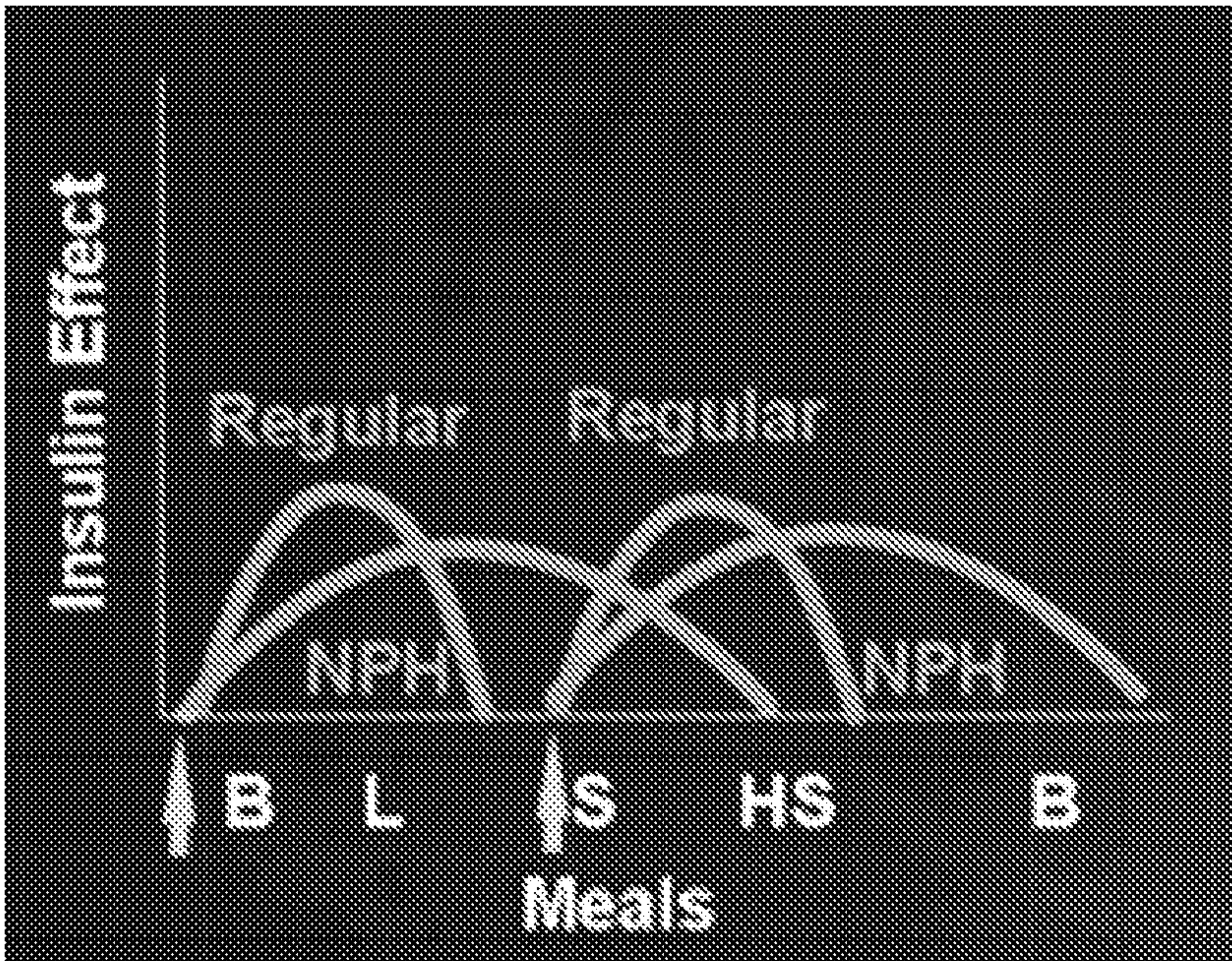


FIGURE 1