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(71) Applicant: MASSACHUSETTS INSTITUTE OF TECHNOLOGY [US/US]; 77 Massachusetts Avenue, Cambridge, MA 02139-4307 (US).

(72) Inventors: PENG, Weng Kung; 1 Create Way, #04-13, Enterprise Wing, Singapore 138602 (SG). HAN, Jongyoon; Massachusetts Institute Of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139 (US). LOH, Tze Ping; 5 Lower Kent Ridge Road, Singapore 119074 (SG).

(74) Agents: FOX, Harold H. et al.; Steptoe & Johnson LLP, 1330 Connecticut Avenue, NW, Washington, DC 20036 (US).

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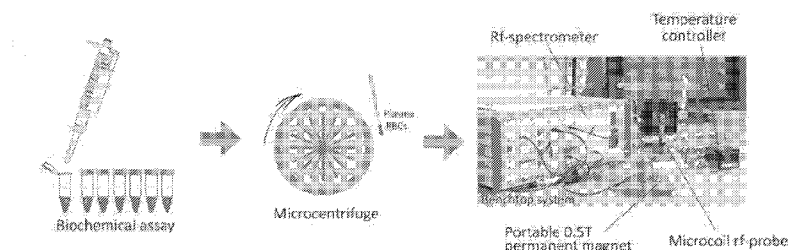


FIG. 1A

(57) Abstract: A low-cost and bench-top magnetic resonance relaxometer can be used for *ex-vivo* biochemical stress tests on plasma/erythrocytes, enabling deep-phenotyping of an individual's oxidative status, susceptibility and capacity.

MICRO MAGNETIC RESONANCE RELAXOMETRY

PRIORITY CLAIM

This application claims priority to U.S. Provisional Application No. 62/152,718, filed
5 April 24, 2015, which is incorporated by reference in its entirety.

TECHNICAL FIELD

This invention relates to magnetic resonance relaxometry.

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BACKGROUND

Diabetes mellitus (DM) is one of the fastest growing health burdens that is projected to affect 592 million people worldwide by 2035. DM is defined by a persistent elevation of glucose concentration. Under chronic hyperglycemic conditions, glucose is non-enzymatically attached to proteins (glycation), which has deleterious effects on their structure and function. Glycated
15 hemoglobin A1c (HbA_{1c}) is the hemoglobin with glucose attached to the N-terminus valine, which reflects the glycemic burden of an individual over the previous 2-3 months. Therefore, it is the recommended biomarker for monitoring the glucose control of DM patients.

Magnetic resonance relaxometry (MRR) is a technique used in nuclear magnetic resonance (NMR) spectroscopy and magnetic resonance imaging (MRI) to acquire spin-echoes
20 of (predominantly) water content of the cells/tissues. Recent advances in NMR system miniaturization have raised the prospect of applying these techniques in point-of-care diagnostic setting. These include immuno-magnetic labeling based (e.g. tumor cells, tuberculosis and magneto-DNA detection of bacteria) and label-free μ MRR detection of various diseases (e.g., oxygenation/oxidation level of the blood and malaria screening).

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SUMMARY

A method of monitoring a disease status can include obtaining a sample, such as a blood sample, from a subject, measuring a longitudinal relaxation time and a transverse relaxation time in the sample, and assessing a redox state of the sample from the longitudinal relaxation time and
30 the transverse relaxation time of the sample.

In one aspect, assessing the redox state can include plotting a magnetic state diagram of a longitudinal relaxation time and a transverse relaxation time, and interpreting the state of the sample based on the location of the sample in the diagram. Assessing the redox state can include calculating a ratio of longitudinal relaxation time to transverse relaxation time of the sample, and
5 comparing the ratio with a predetermined ratio of a reference sample. Measuring the longitudinal relaxation time and the transverse relaxation time can include inserting the sample within a detection coil of a magnetic resonance relaxometry device.

In another aspect, a method of identifying a risk for diabetes mellitus in a patient can include measuring a longitudinal relaxation time and a transverse relaxation time using a
10 magnetic resonance relaxometry device in a sample, such as a blood sample, of the patient, and assigning a risk level to a subject based on a ratio of the longitudinal relaxation time and the transverse relaxation time.

In another aspect, a method of assessing a redox state of a sample can include plotting a magnetic state diagram of a longitudinal relaxation time and a transverse relaxation time,
15 wherein the longitudinal relaxation time and the transverse relaxation time are measured using a magnetic resonance relaxometry device, and interpreting the state of the sample based on the location of the sample in the diagram.

In another aspect, a method of assessing a redox state of a sample can include calculating a ratio of longitudinal relaxation time to transverse relaxation time of the sample, wherein the
20 longitudinal relaxation time and the transverse relaxation time are measured using a magnetic resonance relaxometry device, and comparing the ratio with a predetermined ratio of a reference sample.

The magnetic resonance relaxometry device can include a radio-frequency spectrometer comprising at least one field- programmable gate array chip, a power amplifier electrically
25 connected with the radio-frequency spectrometer and amplifying an electrical output of the radio-frequency spectrometer, thereby producing an amplified electrical signal comprising between about 0.1 Watts and about 10 Watts power, a duplexer configured to isolate the radio-frequency spectrometer from the amplified electrical signal during a receiving mode of the device; a radio-frequency detection probe configured to transmit radio- frequency
30 electromagnetic radiation to excite nuclei under resonance during a transmission mode of the device, the radio-frequency detection probe comprising a detection coil comprising an inner

diameter of less than about 1 millimeter, and at least one magnet supplying an external magnetic field to a detection region of the radio-frequency detection probe, the external magnetic field being less than about 3 Tesla.

Alternatively, the magnetic resonance relaxometry device can include conventional NMR spectroscopy using higher external magnetic field higher than about 3 Tesla.

The sample can be body fluid, tissue or cell samples. In certain embodiments, the body fluid can be blood, sweat, urine or other tissues/cells. In certain embodiments, the blood sample can be plasma or red blood cells. These methods can be used to monitor acute or chronic oxidative stress. The chronic oxidative stress can include diabetes mellitus. The redox state can be a level of oxidative stress; for example, a level of oxidative stress of hemoglobin. Alternatively, the redox state can be a level of nitrosative stress; for example, a level of nitrosative stress of hemoglobin.

A method of monitoring a hemoglobin state using a magnetic state diagram can be represented by a two-dimensional plot of a longitudinal relaxation time and a transverse relaxation time.

A magnetic state diagram for assessing redox state of a sample can include a two-dimensional plot of a longitudinal relaxation time and a transverse relaxation time of the sample.

Other aspects, embodiments, and features will be apparent from the following description, the drawings, and the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1A shows schematic illustration of the MRR assays. FIG. 1B shows standard inversion recovery experiment with Carr–Purcell–Meiboom–Gill (CPMG) detection is used for measuring T_1 relaxations. T_2 relaxations were measured by the same CPMG pulse without the initial 180-degree pulse. FIG. 1C shows redox reactions of the iron-heme in the various oxidation states. FIG. 1D shows various redox states of hemoglobin and its relative T_1 — T_2 coordinates in a MR relaxation ‘state diagram’. FIG. 1E shows the corresponding magnetic states, number of unpaired electron, A—ratio, and iron oxidation state. FIG. 1F shows a quadrant chart of diabetic subject stratified into subgroups based on their oxidative status in association with their glycaemic controls.

FIGS. 2A-2H show nitrite induced ferrous oxidation: redox-titration profile of red blood cells as function of nitrite concentrations in T_1 (FIG. 2A) and T_2 (FIG. 2B) domains. The corresponding concentrations dependent A—ratio (FIG. 2C), and T_1 — T_2 trajectories (FIG. 2D) of the gradual inversion of Fe^{2+} sub-populations to complete formation of Fe^{3+} populations.

5 Time-dependent kinetic profile of ferrous oxidation for nitrite concentrations in (e) T_1 (FIG. 2E) and T_2 (FIG. 2F) domains. FIG. 2G shows the amplitudes of the oscillation depending on the nitrite concentrations. FIG. 2H shows T_1 — T_2 trajectories with various nitrite concentrations.

FIG. 3A shows *in-vivo* redox formation of high-spin met-Hb, low-spin hemichrome and heme metabolism. The equivalent chemically-induced in-vitro environment (in brackets). FIG. 10 3B shows the corresponding T_1 — T_2 trajectories of chemically-induced to form met-Hb and hemichrome, respectively. FIG. 3C shows RBCs baseline readings of non-DM subjects and poor glycaemic control subject for T_2 domain. FIG. 3D shows RBCs baseline readings of non-DM subjects and poor glycaemic control subject for T_1 domain.

FIGS. 4A-4E show the T_1 — T_2 coordinates of MRR measured of Hb before (square) and 15 after (round) nitrite treatment for both the poor (FIG. 4A), and good glycaemic control (FIG. 4B) subjects. Each single point represents the MRR reading of one subject. FIG. 4C shows the corresponding statistical distribution based on A—ratio index for both FIGS. 4A and 4B. FIG. 4D shows characteristic (ROC) analysis that the initial matching baseline between the subjects from poor and good glycaemic group had increased upon nitrite stress. FIG. 4E shows variability 20 of nitrosative susceptibility for good glycaemic control group.

FIGS. 5A-5D show the T_1 — T_2 coordinates of MRR measured plasma baseline readings for each single subject from non-DM subjects (triangle), poor (square) and good (round) glycaemic control subjects. FIG. 5B shows the breakdown details in A—ratio for poor and good glycaemic control subgroups as opposed to non-DM. FIG. 5C shows frequency plot of two 25 binomials overlapped for non-DM subjects and good glycaemic control subjects (right bars) and poor glycaemic control subjects (left bars). FIG. 5D shows ROC-AUC curve.

FIGS. 6A-6E show the T_1 — T_2 diagram of MRR measured plasma serum baseline (square) and plasma pretreated with hydrogen peroxide (round) for subjects with poor glycaemic control (FIG. 6A), good glycaemic control (FIG. 6B), and non-DM (FIG. 6C). Each single point 30 represents a MRR reading taken from one subject. FIG. 6D shows the $A_{\text{peroxidative}}$ index and FIG. 6E shows normalized $A_{\text{baseline}} - A_{\text{peroxidative}}$ for the three glycaemic groups, respectively.

FIGS. 7A-7B show calibration MRR technique with photospectrometry. FIG. 7A shows time dependent kinetic profile for nitrite—induced oxidation of oxy-Hb as measured by MRR and photospectrometry. FIG. 7B shows correlation between MRR and photospectrometry measurements.

FIGS. 8A-8D show limit of detection for photospectrometry technique in met-Hb detection. FIGS. 8A and 8C show photospectrometry spectras for diluted oxy-Hb:met-Hb for (control, 0.5%, 5%, 10%, 20%, 100%). FIGS. 8B and 8D show plot of concentration against the dilution prepared using one tailed student's t-test of paired test to calculate the *P*-value.

FIGS. 9A-9D show limit of detection for MRR technique in met-Hb detection. T_1 — T_2 diagram (left panel) and A—ratio against the met-Hb concentration (%) (right panel) for sample A (FIG. 9A), sample B (FIG. 9B), and sample C (FIG. 9C). FIG. 9D shows T_1 — T_2 diagram (left panel) and T_2 relaxation times (mid panel) and T_1 relaxation times (right panel) against the met-Hb concentration for sample D using one tailed student's t-test of paired test to calculate the *P*-value.

FIGS. 10A-10D show low— and high spin ferric hemoglobin in diabetes mellitus subjects. FIG. 10A shows T_1 - T_2 diagram of RBCs exposed to salicylic (round) and control (square) in *in vitro* environment at different time points. FIG. 10B shows the corresponding A—ratio in time evolution. FIG. 10C shows T_1 - T_2 diagram for RBCs of non DM (square) and DM subjects (round) exposed to sodium salicylic. FIG. 10D shows the corresponding A—ratio.

FIGS. 11A-11D show nitrite concentration selection criteria for nitrite—induced oxidation of RBC assays a short time period. FIG. 11A shows the actual micrograph of the subjects' blood with various nitrite concentrations. FIG. 11B shows A—ratio of randomly assigned subjects taken from a range of HbA_{1c} and their responses over various nitrite stress concentrations on RBCs. FIG. 10C shows concentration of nitrite used against the A—ratio correspond to FIG. 11B. FIG. 11D shows ROC—AUC calculated for each nitrite concentration against the oxy-Hb and met-Hb baseline.

FIGS. 12A-12B show nitrite concentration selection criteria for nitrite—induced oxidation of RBC assays for a very long-time period. FIG. 12A shows A—ratio of randomly assigned subjects taken from a range of HbA_{1c} and their responses over various nitrite stress concentrations on RBCs. FIG. 12B shows the log-log plot of FIG. 12A. FIG. 12C shows ROC—AUC calculated for each nitrite concentration against the oxy-Hb and met-Hb baseline.

FIGS. 13A-13D show A—ratio responses of diabetic subjects to long term *in vitro* exposure to ‘mild’ concentration of H₂O₂ at various time points and concentrations.

FIGS. 14A-14E show peroxide concentration selection criteria for peroxide—induced oxidation of human serum assays. FIG. 14A shows A—ratio of randomly assigned subjects and their responses over various peroxide stress concentrations human serum albumin. FIG. 14B shows concentration of hydrogen peroxide against A—ratio corresponding to FIG. 14A. FIG. 14C shows ROC—AUC calculated for each peroxide concentration against the non-oxidized and non-oxidized serum baseline. FIGS. 14D and 14E show HSA for 2 subjects at various peroxide concentrations at taken by photospectrometry.

FIGS. 15A-15C show *in vitro* glycation of HSA and oxidative status. FIG. 15A shows T₁—T₂ diagram of *in vitro* glycated glucose addition to plasma serum before (blank round) and after (filled round) peroxidative stress. The respective controls without glucose addition are shown in black (square). Each point represents readings taken from three different subjects. FIGS. 15B and 15C show the breakdown of each subject in A_{baseline}—ratio.

FIGS. 16A-16C show correlation of plasma, glycaemic level (fructosamine and HbA_{1c}) and oxidative status.

DETAILED DESCRIPTION

A major pathological effect of diabetes mellitus (DM) is oxidative—nitrosative stress (ONS), which causes many of the secondary complications of diabetes including nephropathy, retinopathy, neuropathy, and cardiovascular diseases. ONS changes the reduction-oxidation state of plasma/erythrocytes, thereby changing their magnetic properties.

HbA_{1c}, while widely used, does not adequately predict complications associated with oxidative stress, which is one of the major pathological processes that promote the complications commonly seen in patients with diabetes, such as nephropathy, retinopathy, neuropathy, and cardiovascular diseases. Oxidative-nitrosative stress can damage nuclei acids, lipids and proteins, which severely compromise cellular health and induce a range of cellular responses leading to cell death. See, Holley, A. & Cheeseman, K. Measuring free radical reactions in vivo. *British Medical Bulletin* **49**, 494-505 (1993), and Maritim, A., Sanders, R. & Watkins, r.J. Diabetes, oxidative stress, and antioxidants: a review. *Journal of biochemical and molecular toxicology* **17**, 24-38 (2003), each of which is incorporated by reference in its entirety. Direct measurement of

oxidative stress and each patient's susceptibility may improve the prediction of disease risks related to oxidative stress in subgroups of DM patients.

Currently, an individual's oxidative stress cannot be easily characterized in detail using available biomarkers. See, Jackson, M.J. An overview of methods for assessment of free radical activity in biology. in *PROCEEDINGS-NUTRITION SOCIETY OF LONDON*, Vol. 58 1001-1006 (Cambridge Univ Press, 1999), and Kopani, M., Celec, P., Danisovic, L., Michalka, P. & Biro, C. Oxidative stress and electron spin resonance. *Clin. Chim. Acta* **364**, 61-66 (2006), each of which is incorporated by reference in its entirety. This has contributed to the lack of understanding of the pathological effects of acute and prolonged exposure to oxidative stress.

Over the years, several methods have been developed to detect the redox properties of the blood, which mainly rely on the optical or magnetic properties of the inorganic iron-chelate of hemoglobin (Hb) and plasma albumin. See, Nonoyama, A. University of South Florida (2004), Shah, S.S., *et al.* A novel cytofluorometric assay for the detection and quantification of glucose-6-phosphate dehydrogenase deficiency. *Sci Rep* **2**, 299, Olsson, M.G., *et al.* Pathological Conditions Involving Extracellular Hemoglobin: Molecular Mechanisms, Clinical Significance, and Novel Therapeutic Opportunities for Hb^{1+1} -Microglobulin. *Antioxidants & Redox Signaling* **17**, 813-846, and Svistunenko, D.A., Patel, R.P., Voloshchenko, S.V. & Wilson, M.T. The globin-based free radical of ferryl hemoglobin is detected in normal human blood. *J. Biol. Chem.* **272**, 7114-7121 (1997), each of which is incorporated by reference in its entirety. Oxidative stress biomarkers are often short-lived and reactive. The reactive oxygen species (ROS) and reactive nitrogen species (RNS) can be detected via electron spin resonance (ESR). See, Emanuel, N.M., Saprin, A.N., Shabalkin, V.A., Kozlova, L.E. & Krugljakova, K.E. Detection and investigation of a new type of ESR signal characteristic of some tumour tissues. *Nature* **222**, 165-167 (1969), and Takeshita, K. & Ozawa, T. Recent progress in in vivo ESR spectroscopy. *J Radiat Res* **45**, 373-384 (2004), each of which is incorporated by reference in its entirety. The ESR approach is hampered by inherent sample instability issues, and hence has low reproducibility and limited sensitivity. Stable molecular products formed from reactions with ROS/RNS, such as the oxidation targets (e.g., lipid, protein, acid nucleic) are measurable using a range of spectrophometric assays and mass spectrometry (MS). See, Nikov, G., Bhat, V., Wishnok, J.S. & Tannenbaum, S.R. Analysis of nitrated proteins by nitrotyrosine-specific affinity probes and mass spectrometry. *Analytical biochemistry* **320**, 214-222 (2003), and Jiang, T., Zhou, X.,

Taghizadeh, K., Dong, M. & Dedon, P.C. N-formylation of lysine in histone proteins as a secondary modification arising from oxidative DNA damage. *Proceedings of the National Academy of Sciences* **104**, 60-65 (2007), each of which is incorporated by reference in its entirety. Nevertheless, fluorescent-staining often causes cell-toxicity, and therefore the assays
 5 may not provide information that reflects in vivo conditions. See, Spasojević, I., Bajić, A., Jovanović, K., Spasić, M. & Andjus, P. Protective role of fructose in the metabolism of astroglial C6 cells exposed to hydrogen peroxide. *Carbohydrate research* **344**, 1676-1681 (2009), and Buckman, J.F., *et al.* MitoTracker labeling in primary neuronal and astrocytic cultures: influence of mitochondrial membrane potential and oxidants. *Journal of neuroscience methods* **104**, 165-
 10 176 (2001), each of which is incorporated by reference in its entirety. Ultraviolet-visible light spectroscopy has poor spectral resolution, and sensitivity and globin-associated free radical in Hb is not optically visible (Supplementary Figs. 7-9). See, Della Longa, S., *et al.* Iron site structure of two irreversible hemichromes from human hemoglobin, untreated and oxidized to sulfoxide at MetD6 (55) beta. *Biochimica et biophysica acta* **1294**, 72-76 (1996), and Rifkind,
 15 J.M., Abugo, O., Levy, A. & Heim, J. Detection, formation, and relevance of hemichromes and hemochromes. *Methods in enzymology* **231**, 449-480 (1993), each of which is incorporated by reference in its entirety. MS-based analysis of ROS/RNS reaction products is a powerful and sensitive technique to reveal detailed chemistry of these species, yet requires substantial sample preparation and therefore difficult to be employed as a rapid screening tool. See, Aebersold, R. &
 20 Mann, M. Mass spectrometry-based proteomics. *Nature* **422**, 198-207 (2003), which is incorporated by reference in its entirety.

Disclosed herein is a method to rapidly quantify the composite redox state of the hemoglobin/plasma with a bench-top sized micro magnetic resonance relaxometry (μ MRR) system using a T_1 (longitudinal relaxation time) - T_2 (transverse relaxation time) diagram (FIGS.
 25 1A-F).

Also disclosed is a method of monitoring a disease status can include obtaining a sample from a subject, measuring a longitudinal relaxation time and a transverse relaxation time in the sample, and assessing a redox state of the sample from the longitudinal relaxation time and the transverse relaxation time of the sample. The sample can be body fluid, tissue or cell samples. In
 30 certain embodiments, the body fluid can be blood, sweat, or urine. In certain embodiments, the blood sample can be plasma/serum or red blood cells. The method can be used to monitor acute

or chronic oxidative stress. The chronic oxidative stress can include diabetes mellitus. The redox state can be a level of oxidative stress; for example, a level of oxidative stress of hemoglobin. Alternatively, the redox state can be a level of nitrosative stress; for example, a level of nitrosative stress of hemoglobin.

5 In one aspect, assessing the redox state can include plotting a magnetic state diagram of a longitudinal relaxation time and a transverse relaxation time, and interpreting the state of the sample based on the location of the sample in the diagram. Assessing the redox state can include calculating a ratio of longitudinal relaxation time to transverse relaxation time of the sample, and comparing the ratio with a predetermined ratio of a reference sample. Measuring the longitudinal
10 relaxation time and the transverse relaxation time can include inserting the blood sample within a detection coil of a magnetic resonance relaxometry device.

 In another aspect, a method of identifying a risk for diabetes mellitus in a patient can include measuring a longitudinal relaxation time and a transverse relaxation time using a magnetic resonance relaxometry device in a blood sample of the patient, and assigning a risk
15 level to a subject based on a ratio of the longitudinal relaxation time and the transverse relaxation time.

 In another aspect, a method of assessing a redox state of a sample can include plotting a magnetic state diagram of a longitudinal relaxation time and a transverse relaxation time, wherein the longitudinal relaxation time and the transverse relaxation time are measured using a
20 magnetic resonance relaxometry device, and interpreting the state of the sample based on the location of the sample in the diagram.

 In another aspect, a method of assessing a redox state of a sample can include calculating a ratio of longitudinal relaxation time to transverse relaxation time of the sample, wherein the longitudinal relaxation time and the transverse relaxation time are measured using a magnetic
25 resonance relaxometry device, and comparing the ratio with a predetermined ratio of a reference sample.

 In another aspect, a method of monitoring a hemoglobin state using a magnetic state diagram can be represented by a two-dimensional plot of a longitudinal relaxation time and a transverse relaxation time.

30 A magnetic state diagram for assessing redox state of a sample can include a two-dimensional plot of a longitudinal relaxation time and a transverse relaxation time of the sample.

A biosensor, palm-sized device and method based on magnetic resonance relaxometry is described in WO 2012/118,442, which is incorporated by reference in its entirety. Vo, N., *et al.* also described a highly integrated, low cost, palm-top sized magnetic resonance relaxometry system for rapid blood screening in *The 15th International Conference on Biomedical Engineering*, Vol. 43, 558-561 (Springer International Publishing), which is incorporated by
5 reference in its entirety.

The magnetic resonance relaxometry device can include a radio-frequency spectrometer comprising at least one field- programmable gate array chip, a power amplifier electrically connected with the radio-frequency spectrometer and amplifying an electrical output of the
10 radio-frequency spectrometer, thereby producing an amplified electrical signal comprising between about 0.1 Watts and about 10 Watts power, a duplexer configured to isolate the radio-frequency spectrometer from the amplified electrical signal during a receiving mode of the device; a radio-frequency detection probe configured to transmit radio- frequency electromagnetic radiation to excite nuclei under resonance during a transmission mode of the
15 device, the radio-frequency detection probe comprising a detection coil comprising an inner diameter of less than about 1 millimeter, and at least one magnet supplying an external magnetic field to a detection region of the radio-frequency detection probe, the external magnetic field being less than about 3 Tesla. Alternatively, the magnetic resonance relaxometry device can include conventional NMR spectroscopy using higher external magnetic field higher than about
20 3 Tesla.

This highly sensitive and targeted approach (as well as composite measurement) accurately detect and quantify the redox (and hence oxidative/nitrosative) state of blood samples. The non-destructive nature of the MRR measurement allows oxidative stress to be artificially introduced in *ex vivo* environment using different biochemical compounds (*e.g.* nitrite, peroxide,
25 sodium salicylic) in a controlled manner to the cells (FIG. 1C). This allows functional assessment of the oxidative susceptibility, tolerance and capacity of a subject. This yields significantly richer and clinically useful information about the oxidative health of an individual, which is difficult to achieve with the routine biomarkers. A T_1 — T_2 magnetic state diagram is developed to enumerate the various redox states of the Hb (*e.g.*, Fe^{2+} , Fe^{3+} , Fe^{4+} , and globin-associated radical Fe^{4+}) and plasma (FIG. 1D). This state diagram allows visualization and
30 identification of the intermediate redox states and the transient dynamic pathways of the blood.

This technique was applied on archived human blood samples to stratify diabetic subjects into subgroups based on their oxidative status in association with glycaemic control (FIG. 1F). Assessment of oxidative status by measuring the redox state of the blood was shown to be highly time- and patient-specific, potentially unlocking information that is critical for clinical diagnostic, monitoring and prognostic purposes. This technology was demonstrated in a clinical setting to stratify DM (n=245) and non-DM (n=32) subjects into sub-groups based on their ONS in association with glycaemic profile. These parameters may serve as additional risk stratification tools.

This is the first disclosure of the unique magnetic resonance properties of the various hemoglobin states and a magnetic state diagram to monitor them. The measurement of redox properties in plasma/erythrocytes can provide a useful parameter for functional phenotyping of many biological pathways leading to the understanding of diseases onset/progression and hence its application to disease diagnosis, prognosis and monitoring.

The platform presented here has several innovative features and is readily adaptable into clinical use. Firstly, the miniaturized platform used here is portable and the proposed assays requires minimal processing steps, ultra low-cost and can be performed by minimally operator training. See, Vo, N., *et al.* Highly Integrated, Low Cost, Palm-Top Sized Magnetic Resonance Relaxometry System for Rapid Blood Screening. in *The 15th International Conference on Biomedical Engineering*, Vol. 43 558-561 (Springer International Publishing), Sun, N., *et al.* Palm NMR and 1-chip NMR. *Solid-State Circuits, IEEE Journal of* **46**, 342-352, Peng, W.K., Chen, L. & Han, J. Development of miniaturized, portable Magnetic Resonance Relaxometry System for Point-of-Care Medical Diagnosis. *Rev Sci Instru* **83**(2012), and Haun, J.B., *et al.* Micro-NMR for rapid molecular analysis of human tumor samples. *Science Translational Medicine* **3**, 71ra16, each of which is incorporated by reference in its entirety. The high sensitivity can be attributed to the micron-sized detection coil and optimized ultra-short echo time implemented in this work. Only a minute amount of blood sample volume (<10—20 μ L) is needed for each test. This allows the collection of sample using minimally invasive technique such as finger prick.

Secondly, the non-destructive nature of magnetic resonance introduced a number of *in-vitro* new functional assays that yielded parameters about the oxidative status of an individual, which may be clinically useful. It probes the primary redox event as compared to the current

gold-standard biomarker, isoprostanes, which is a downstream marker and with other confounding factors. The use of isoprostanes as biomarker of oxidative status for correlation with disease outcome has so far yielded conflicting results in cross-sectional versus longitudinal studies. See, Lee, R., Margaritis, M., Channon, K. & Antoniadou, C. Evaluating oxidative stress in human cardiovascular disease: methodological aspects and considerations. *Current medicinal chemistry* **19**, 2504 (2012), which is incorporated by reference in its entirety. Furthermore, they are static biomarkers that provide snapshots of the oxidative status of biological samples representing the *in vivo* condition of the subject at the point of collection. To accurately measure these molecules, laborious technique such as gas— or liquid-chromatography mass spectrometry has to be employed, limiting its utility as diagnostic tools.

This accurate and rapid technique for quantification of oxidative stress can be included in future risk stratification models where subjects with single or multiple complications can be streamlined with a single oxidative index. This method can be applied to assess oxidative stress in a systematic manner for various diseases and a wide range of hematology applications, both the acquired and congenital diseases such as enzymatic deficiency (e.g., G6PD), Hb synthesis defects (e.g., Thalassemia), and Hb molecular defects (e.g., sickle cells anemia, unstable Hb).

EXAMPLES

T₁—T₂ State-Diagram: Redox States of blood

Redox homeostasis is a fundamental biological process, which maintains the balance between ambient anti-oxidant and pro-oxidant activities. See, Cimen, M.Y. Free radical metabolism in human erythrocytes. *Clin. Chim. Acta* **390**, 1-11 (2008), which is incorporated by reference in its entirety. Blood, in particular the iron-containing heme, which has partially filled *d*-orbital shells (and hence allows the formation of various redox states) that act as an electron reservoir (see, Jomova, K. & Valko, M. Advances in metal-induced oxidative stress and human disease. *Toxicology* **283**, 65-87, and Hartwig, A. Recent advances in metal carcinogenicity. *Pure Appl. Chem.* **72**, 1007-1014 (2000), each of which is incorporated by reference in its entirety), is an important biological agent in ameliorating oxidative stress. On the other hand, oxidized Hb themselves can act as sources of electrons contributing to oxidant built-up.

FIG. 1A shows schematic illustration of the MRR assays. Once the patient's blood is collected via venipuncture or finger prick, necessary biochemical assay is performed in blood

aliquots. Chemical reagent (e.g., nitrite, peroxide, acid salicylic) is mixed with the fresh blood and incubated for intervals 10 minutes (unless mentioned otherwise) in selected concentration. Microcapillary tubes were then used to sample the redox state of the packed RBCs/plasma. Standard centrifugal force (3000 g, 1 minute) was used to separate and concentrate the packed
 5 RBCs from the buffer to avoid possible hematocrit variation in patients. The capillary tubes were then slotted into the rf-probe for MRR read-out, which typically requires less than 5 minutes. The portable micro MRR system developed in this work consists of a bench-top console, detection circuit-coil mounted on a micro-stage and a palm-sized 0.5T permanent magnet, which is maintained in a temperature controller to maintain the magnetic stability.

10 FIG. 1B shows standard inversion recovery experiment with CPMG detection is used for measuring T_1 relaxations. T_2 relaxations were measured by the same CPMG pulse without the initial 180-degree pulse. In order to obtain high signal-to-noise ratio under strongly inhomogeneous magnetic environment, an array of echoes (a few thousands) within a very short echo interval (in the order of μs) were used to acquire spin-echoes from in less than 4 μL
 15 sample volume of packed RBCs or plasma.

FIG. 1C shows redox reactions of the iron-heme in the various oxidation states: Fe^{2+} , Fe^{3+} , Fe^{4+} and globin-radical Fe^{4+} , which were chemically-induced in in-vitro environment. The haemoglobins were in two-possible magnetic states: diamagnetic (red) and paramagnetic state (blue).

20 FIG. 1D shows various redox states of hemoglobin and its relative T_1 — T_2 coordinates in a MR relaxation ‘state diagram’. The coordinates were oxy-Hb ($T_2=152\pm10$, $T_1=628\pm25$), deoxy-Hb ($T_2=124\pm12$, $T_1=622\pm15$), met-Hb ($T_2=102\pm2$, $T_1=198\pm5$), ferryl-Hb ($T_2=139\pm10$, $T_1=522\pm20$), oxoferryl-Hb ($T_2=34.2\pm4$, $T_1=95.2\pm6$), nitrosyl-Hb ($T_2=121\pm4$, $T_1=204\pm8$), and hemichrome ($T_2=108\pm4$, $T_1=603\pm11$). The corresponding magnetic states, number of unpaired
 25 electron, A—ratio, and iron oxidation state in shown in Table in FIG. 1E.

FIG. 1F shows a quadrant chart of diabetic subject stratified into subgroups based on their oxidative status in association with their glycaemic controls

Here, various redox states of the blood were chemically induced (FIG. 1C), characterized and represented in a T_1 - T_2 magnetic resonance relaxation state diagram (FIG. 1D). Each
 30 hemoglobin species has specific oxidation states (e.g., Fe^{2+} , Fe^{3+} , Fe^{4+} , globin-associated radical of Fe^{4+} or its’ corresponding complexes) that are bound to specific neighboring proteins, and

dissipate energy via unique relaxations mechanism in both the longitudinal (T_1) and transverse (T_2) relaxation frames. This creates a unique pair of T_1 - T_2 relaxometry coordinates for each redox species. Oxyhemoglobin (oxy-Hb), which contains the lowest reduced ferrous (Fe^{2+}) state, is the predominant Hb species in circulation. It is assigned the origin (center) coordinate, which
 5 divide the MR state diagram into four quadrants. Most of the redox reactions of the hemoglobin occur in quadrant-1 (short relaxation times in the order of ms) and is mainly due to the semi-solid structure of RBCs. By contrast, the redox reaction of plasma albumin, which involves unbound water-proton, has a much longer relaxation time and occurs in quadrant-2.

The electrons in the d sub-orbitals of iron in hemoglobin can exist in various paired or unpaired
 10 states, allowing them to exist in diamagnetic and paramagnetic states, respectively. Hb with at least one unpaired electron, *i.e.* deoxygenated hemoglobin (deoxy-Hb), methemoglobin (met-Hb), hemichrome (HC), nitrosyl hemoglobin (nitrosyl-Hb), and oxo-ferryl radical exhibit paramagnetism and has much larger bulk magnetic susceptibility than its diamagnetic counterparts (oxy-Hb, and ferryl-Hb) (FIGS. 1D and 1E). The magnetic relaxivity contributed by
 15 any paramagnetic ion is highly dependent on its spin state, and is directly proportional to $S(S+1)$, where S is the spin quantum number of the total electron spin. Each of the Hb oxidation states has a specific normalized relaxation constant (A —ratio= T_1/T_2) identifier (FIG. 1E).

Nitrite-induced Ferrous Oxidation

FIGS. 2A-H show nitrite induced ferrous oxidation: Redox-titration profile of red blood
 20 cells as function of nitrite concentrations in T_1 (FIG. 2A) and T_2 (FIG. 2B) domains. The incubation times were 10 minutes. The control baseline reading were (T_{20} =149.5, T_{10} =621.3) ms, which is the readings for oxy-Hb without any nitrite exposure. The corresponding concentrations dependent A —ratio (FIG. 2C), and T_1 — T_2 trajectories (FIG. 2D) of the gradual inversion of Fe^{2+} sub-populations to complete formation of Fe^{3+} populations. Time-dependent kinetic profile of
 25 ferrous oxidation for nitrite concentrations (500 μ M, 4mM, 8mM and 10mM) in T_1 (FIG. 2E) and T_2 domains (FIG. 2F). The corresponding time-dependent A —ratio (FIG. 2C), and T_1 — T_2 trajectories (FIG. 2D) in the state diagram. The readings were indicated in mean and standard mean error (s.e.m) from three samplings.

Freshly collected blood containing predominantly the oxygenated Hb are oxidized *in*
 30 *vitro* to met-Hb in the presence of sodium nitrite, and were independently verified by spectrophotometry (FIG. 7). Redox titration profile showed a strong dose-dependent curve where

both T_1 and T_2 relaxation times reduced gradually as progressively higher proportion of RBCs is oxidized and hence increases the volume paramagnetic susceptibility, when the nitrite concentrations were increased from 50nM to 10mM (FIGS. 2A and 2B). As the blood sample transformed to a complete paramagnetic state ($T_2=92.8\text{ms}$, $T_1=190.0\text{ms}$) from the initial diamagnetic states ($T_2=149.0\text{ms}$, $T_1=620.0\text{ms}$), the A—ratio dropped from 4.16 to 2.02 (FIG. 2C). This causes the T_1 — T_2 trajectory to move in quadrant-1 as the volume paramagnetic susceptibility increased (FIG. 2D).

The dose-dependent reaction was lost when excess of nitrite ($>10\text{ mM}$) was introduced. This indicated that the oxidant concentration had exceeded the biochemical homeostasis mechanism. At much lower concentration ($<100\text{ }\mu\text{M}$), there was little or no change in the bulk magnetic state of the RBCs, as the majority of the RBCs were able to restore their original reduced state. Interestingly, steep transitional oxidation zone was observed within a very narrow range of nitrite concentration; from 1mM to 8mM, which reflected the redox homeostatic responses within the concentration where the cells were viable. This was crucial to the understanding of the functioning of RBCs at cellular and subpopulation level (FIGS. 2A-2C). Similar trends were observed in subjects of different age and gender, which provided an understanding of the degree of inter-individual variability (FIGS. 10A-D).

Further evidence of redox homeostasis were observed in time-dependent kinetic profiles (FIGS. 2E-2F) over a range of nitrite concentrations (500 μM , 4mM, 8mM and 10mM). In general, measured T_1 and T_2 values changed in an oscillatory manner over time. This may suggests an active mechanism to regulate cell redox homeostasis. The alpha-Hb are known to have much higher oxidative susceptibility than beta-Hb. Furthermore, the RBCs may have reduced antioxidant capacity as they age, thereby forming a subpopulation of cell with disproportionately low antioxidant capacity. See, Bernhardt, I. & Ellory, J. Red cell membrane transport in health and disease. (2003), which is incorporated by reference in its entirety.

The amplitudes of the oscillation decreased as the nitrite concentration was increased from 500 μM to 4mM (FIG. 2G). At much higher nitrite concentration ($>10\text{mM}$), the reaction curve decayed rapidly in exponential manner with an increasingly dampened oscillation. Interestingly, the corresponding kinetic profiles followed an identical path over time in the T_1 — T_2 trajectories as the nitrite concentration was increased (FIG. 2H). The oxidation process drove all the trajectories toward a common coordinate ($T_2= 92.8\text{ms}$, $T_1= 190.0\text{ms}$), where full met-Hb

conversion was achieved eventually. For low nitrite concentration (e.g., 500 μ M) however, the T_1 — T_2 trajectory circulated around the origin and did not reach the eventual met-Hb coordinates at the time intervals shown in this work.

Deep Phenotyping of Nitrosative/Oxidative Stress in Diabetes Mellitus Subjects

5 A cross-sectional study was carried out to further stratify DM subjects based on their oxidative status. DM subjects (n=426) who had HbA_{1c} measured in the outpatient clinic as part of their clinical care were included in this study. These subjects have HbA_{1c} ranged from 4% to 16%, which were classified as good glycaemic control ($\leq 7.0\%$ HbA_{1c}) and poor glycaemic control ($\geq 8.0\%$ HbA_{1c}) sub-groups based on the criteria set by WHO. Healthy young male
10 subjects (n=35) between 21 to 40 years subjects with no past history of DM with fasting glucose <7.0 mmol/L, and $(5.16 \pm 0.32)\%$ of HbA_{1c}, with the body mass index below 23.5 kg/m^2 were recruited as controls. Freshly drawn blood obtained via venipuncture was spun down to separate the RBCs and plasma. MRR measurements on the hemoglobin and plasma (both the baseline and biochemical stress test) were performed blindly on freshly collected blood (or otherwise stored
15 under 4°C within 1—2 hours). Other hematology tests were carried out in parallel.

Baseline study: Oxidative Status of Glycated Hb and Hb in RBCs

FIG. 3A shows *in-vivo* redox formation of high-spin met-Hb, low-spin hemichrome and heme metabolism. The equivalent chemically-induced *in-vitro* environment (in brackets). FIG. 3B shows the corresponding T_1 — T_2 trajectories of chemically-induced with 10mM nitrite and
20 0.15M SLS, to form met-Hb and hemichrome, respectively. The parenthesis indicating the relative coordinates (T_2 , T_1 , A—ratio). FIGS. 3C and 3D show RBCs baseline readings of non-DM subjects (blue, n=23) and poor glycaemic control subjects (red, n=68) for T_2 and T_1 domains, respectively. Each single point represents the MRR reading of one subject. The breakdown details of poor ($>8\%$ and $>10\%$ HbA_{1c}) and good glycaemic control ($<7\%$ HbA_{1c})
25 subgroups as opposed to non-DM subjects in T_2 (FIG. 3C) and T_1 (FIG. 3D) domains.

Mapped baseline of hemoglobin in intact red blood cells in T_1 — T_2 state diagram showed an elevation in met-Hb and HC concentration are more common in subjects with poor glycaemic control compared with non-DM subjects (FIG. 3A). DM subjects with good glycaemic control had slightly elevated T_2 values (p -value <0.05), but difference in T_1 value was not statistically
30 significant ($p>0.05$) compared with non-DM subjects (FIG. 3B-3D). Non-DM subjects had met-Hb concentrations that were less than 2% (FIGS. 2D and 9). Ferric-Hb concentration was

markedly elevated in DM subjects with poor glycaemic control, particularly in subjects with HbA_{1c} of concentration >10% (FIGS. 3B-3D and 10).

Ex-vivo Nitrosative Stress Test on Glycated-Hb

To further evaluate the ability of individual's RBCs to tolerate the nitrosative stress, the RBCs were artificially challenged with nitrite. Fresh RBCs were incubated with 6mM sodium nitrite for 10 min, washed three times to stop the reaction and finally resuspended in 1x PBS for MRR measurements. The oxidant concentration chosen was the viable homeostatic range unique to each individual depending of his or her (patho)physiological condition (FIGS. 11-13). MRR measurements were assessed before (square) and after (circle) the stress test.

DM subjects with poor (n=12) and good (n=29) glycaemic control group with similar matching RBCs baseline (squares in FIGS. 4A-4B) were chosen for this test. Lower anti-nitration capacity (or increased in nitrosative stress susceptibility) was indicated by an increase in met-Hb formation (circles) and hence the lower the A_{nitrosative}-ratio value (FIGS. 2A-H). FIGS. 4A-E show the T₁—T₂ coordinates of MRR measured of Hb before (square) and after (round) 6mM nitrite treatment for both the poor (FIG. 4A) and good glycaemic control (FIG. 4B) subjects. Each single point represents the MRR reading of one subject. FIG. 4C shows the corresponding statistical distribution based on A—ratio index for both FIG. 4A and FIG. 4B.

DM subjects vary markedly in their nitrosative susceptibility despite having similar matching baseline; with DM subjects of poor glycaemic control being more susceptible to nitrite-induced oxidation as compared to its counterpart with good glycaemic control (FIG. 4C). Receiver Operating Characteristic (ROC) analysis showed that the initial matching baseline (AUC < 0.39) between the subjects from poor and good glycaemic group had increased (AUC > 0.70) upon nitrite stress (FIG. 4D). Due to structural modification of hemoglobin as a result of increased glycation, HbA_{1c} is less stable and more prone to oxidation, in agreement with observation reported elsewhere. See, Moussa, S. Oxidative stress in diabetes mellitus. *Romanian J Biophys* **18**, 225-236 (2008), and Tarburton, J. Amyl Nitrite Induced Hemoglobin Oxidation Studies in Diabetics and Non-diabetics Blood. *J Diabetes Metab* **4**, 2 (2013), each of which is incorporated by reference in its entirety.

The spread were however large for good glycaemic control group, which suggest a large subject variability of nitrosative susceptibility, despite having similar glycaemic level (FIG. 4E). Using the nitrosative susceptibility (A_{nitrosative}-ratio), which could be derived hypothetically from

this study and the traditional index of glycaemic control (HbA_{1c}), DM subjects could be stratified into four distinct quadrants (Q1—Q4). This approach singled out a minority group in Q3, who had good glycaemic control, and yet nitrosative stress the A_{nitrosative}-ratio threshold that was 75-percentile of that typical to DM subjects with poor glycaemic control. Further large-scale prospective study in different population would be needed, to establish predictive power of these new measurements combined with glycemic marker.

Baseline Study: Glycation and Glycooxidation of Plasma serum

Increased blood glucose promotes non-enzymatic glycation of plasma proteins, which include the albumin, alpha-crystalline, collagen, and low-density lipoprotein. See, Lodovici, M., *et al.* Oxidative DNA damage and plasma antioxidant capacity in type 2 diabetic patients with good and poor glycaemic control. *Mutation Research/Fundamental and Molecular Mechanisms of Mutagenesis* **638**, 98-102 (2008), Lee, R., Margaritis, M., Channon, K. & Antoniadis, C. Evaluating oxidative stress in human cardiovascular disease: methodological aspects and considerations. *Current medicinal chemistry* **19**, 2504 (2012), and Bourdon, E., Loreau, N. & BLACHE, D. Glucose and free radicals impair the antioxidant properties of serum albumin. *The FASEB journal* **13**, 233-244 (1999), each of which is incorporated by reference in its entirety. However, a large proportion of total serum protein is attributable to serum albumin. See, Roche, M., Rondeau, P., Singh, N.R., Tarnus, E. & Bourdon, E. The antioxidant properties of serum albumin. *FEBS letters* **582**, 1783-1787 (2008), which is incorporated by reference in its entirety. Glycation and oxidative damage cause protein modifications and hence its functionality. MRR baseline and peroxidative stress measurements were performed on the plasma serum at room temperature. See, Yilmaz, A., Ulak, F. & Batun, M. Proton T₁ and T₂ relaxivities of serum proteins. *Magnetic resonance imaging* **22**, 683-688 (2004), which is incorporated by reference in its entirety. Each T₁-T₂ coordinate represented the composite redox properties (see, Bernhardt, I. & Ellory, J. Red cell membrane transport in health and disease. (2003), and Moussa, S. Oxidative stress in diabetes mellitus. *Romanian J Biophys* **18**, 225-236 (2008), each of which is incorporated by reference in its entirety) of one subject (FIG. 5A). FIG. 5A shows the T₁—T₂ coordinates of MRR measured plasma baseline readings for each single subject from non-DM subjects (triangle, n=24), poor (square, n=37) and good (round, n=55) glycaemic control subjects. Plasma baseline T₁-T₂ coordinates of the DM subjects (both the poor and good glycaemic control) concentrating in the lower quadrants were well separated from the non—DM

subjects. FIG. 5B shows the breakdown details in A—ratio for poor (>8% and >10% HbA_{1c}) and good glycaemic control (<7% HbA_{1c}) subgroups as opposed to non-DM. Median A-ratio for plasma baseline in this cohort were 2.49, 2.36, 2.32 and 2.12, for DM subjects with >10% HbA_{1c}, >8% HbA_{1c}, <7% HbA_{1c}, and non-DM, respectively (FIG. 5B). The combined frequency distributions were as shown in FIG. 5C.

The marked reduction in relaxation states was attributed to an increase in glycation and glycoxidation of the serum albumin. As a result of increased glycation (FIG. 15A) and protein oxidative damage (e.g. protein crosslinking) the bulk water proton of mobility (see, Grösch, L. & Noack, F. NMR relaxation investigation of water mobility in aqueous bovine serum albumin solutions. *Biochimica et Biophysica Acta (BBA)-Protein Structure* **453**, 218-232 (1976), which is incorporated by reference in its entirety) was restricted, hence the reduction in T₁ and T₂ relaxation times. T₂ relaxation however reduced much faster than T₁ relaxation resulting in an increment in A_{baseline}—ratio, which had positive correlation with respect to HbA_{1c} (R²>0.72) (FIG. 5D). Similar trends were observed *in vitro*, which confirm the effect of glycation (FIGS. 15A and 15B) and glycoxidation effect (FIG. 15C). Interestingly, ROC analysis indicates DM subjects with good-glycaemic control and non-DM subjects were 0.85 (not shown), much higher than the one observed in RBCs (AUC<0.39 in FIG. 4D). This suggests that pathological footprint of hyperglycemia were more prominent in extracellular plasma as opposed to RBCs. See, Lodovici, M., *et al.* Oxidative DNA damage and plasma antioxidant capacity in type 2 diabetic patients with good and poor glycaemic control. *Mutation Research/Fundamental and Molecular Mechanisms of Mutagenesis* **638**, 98-102 (2008), which is incorporated by reference in its entirety.

Peroxide-induced Oxidation Analysis: Total Anti-oxidant Capacity of Plasma Serum in Diabetes Mellitus Subjects

In order to evaluate the total anti-oxidant capacity of plasma serum towards oxidation, the plasma serum was artificially challenged with hydrogen peroxide on subjects with poor glycaemic control (n=52), good glycaemic control (n=18), and non-DM (n=21) as control (FIGS. 6A-E). Hydrogen peroxide solution was added into the freshly drawn plasma (10% v/v) for an incubation time of 10 min (FIGS. 14A-E). MRR measurements were performed before (squares) and after (circles) mixing (FIGS. 6A-6C).

Stress—test results revealed a large spread of T_1 - T_2 coordinates for DM subjects (FIGS. 6A and 6B), who varied markedly in their peroxidative susceptibility as compared to non—DM subjects (FIG. 6C). Lower anti-oxidant capacity (or increase in peroxidative stress susceptibility) of plasma is indicated by reduction in T_1 and T_2 relaxation coordinates (circles). As more oxidized plasma was formed, the T_1 relaxation time reduced much faster than T_2 relaxation time, and hence the reduction in $A_{\text{peroxidative}}$ -ratio (FIG. 6D). This was in agreement with *in vitro* study (FIG. 15C).

DM subjects had much higher plasma peroxidative susceptibility as compared to non-DM counterparts (FIG. 6E). The normalized plasma peroxidative stress susceptibility can be loosely defined by A_{baseline} —ratio subtracting the $A_{\text{peroxidative}}$ —ratio (FIG. 6E). The peroxidative susceptibility was also found to be positively correlated to glycaemic levels, both the HbA_{1c} (FIG. 16C) and fructosamine level (FIG. 16D). Note that the plasma baseline (black) measurements of this cohort had similar positive trend with respect to glycaemic levels (FIG. 6D) were in agreement with the previous cohort measured independently (FIGS. 5A-D).

Exposure to peroxy compound led to increased formation of disulfide bonding in albumin and human non-mercaptalbumin were reported in several other pathologic conditions. See, Oettl, K. & Stauber, R. Physiological and pathological changes in the redox state of human serum albumin critically influence its binding properties. *British journal of pharmacology* **151**, 580-590 (2007), SOGAMI, M., *et al.* HPLC- studies on nonmercapt- mercapt conversion of human serum albumin. *International journal of peptide and protein research* **25**, 398-402 (1985), and Kadota, K., Yui, Y., Hattori, R., Murohara, Y. & Kawai, C. Decreased sulfhydryl groups of serum albumin in coronary artery disease. *Japanese circulation journal* **55**, 937-941 (1991), each of which is incorporated by reference in its entirety. The peroxidative susceptibility measurements (FIG. 6E), independent of HbA_{1c} stratify the DM subjects into sub-groups which provides insight into the oxidative status (susceptibility and damage) of each individual patients.

Calibration of MRR measurements with photospectrometry

Freshly drawn blood were washed, resuspended into 1x PBS and exposed to 6mM nitrite. The amount of oxy-Hb to met-Hb conversion was measured independently using MRR and photospectrometry techniques at y one minute intervals. FIG. 7A shows Time dependent kinetic profile for nitrite—induced oxidation of oxy-Hb as measured by MRR (n=3) and photospectrometry (n=5 to 8). 6mM nitrite concentration was used and the RBCs were sampled

and measured at every 1 min intervals. Error bars were standard deviation. Note that the error bars for MRR measurements were too small ($<5\%$). The kinetic profile of met-Hb formation over time (FIG. 7A) as monitored by MRR mapped closely to the photospectrometry technique ($R^2 > 0.97$) (FIG. 7B). The time-dependant oscillatory decay profile was also observed here, similarly to the one observed in another donor (FIGS. 2A-H). It is also worth noting that the sensitivity dropped (as indicated by the error bars) for photospectrometry measurement as the met-Hb concentration reduce (FIG. 7B), which suggests low optical absorption properties of met-Hb. We further investigated and compared the limit of detection for both the optical— and magnetic based methods (FIGS. 8A-D).

Limit of detection: Comparison between MRR and Photospectrometry technique

Met-Hb were spiked into oxy-Hb at various concentrations from 0.0005% to 100% and were measured simultaneously using both photospectrometry (FIGS. 8A-D) and MRR system (FIGS. 9A-D). The concentration (μM) were calculated from two absorbance peaks at 577nm and 630nm and based 1mm optical path, the $[\text{oxy-Hb}] = 6.6A_{577} - 8A_{630}$ and $[\text{met-Hb}] = 27.9A_{630} - 0.3A_{577}$. Repeated sampling ($n > 8$) was carried out for each dilution. The limit-of-detection (P -value < 0.05) for photospectrometry technique was found to be approximately 5%, and 1% met-Hb for sample A and B, respectively. The optical spectra for low concentration of met-Hb ($< 1\%$) were poorly resolved (FIGS. 8A and 8C), which is due to the attributes of low optical absorption of the oxidized hemoglobin at 630 nm wavelength.

For MRR measurement, the dilution experiment was repeated four times on four different blood samples (sample A, sample B, sample C and sample D). Paramagnetic susceptibility of met-Hb causes reduction in T_1 , T_2 relaxations and A —ratio. The results in FIGS. 9A-D suggest that depending on the condition of the blood and donors variability, a limit-of-detection (P -value < 0.05) of approximately 0.0005% can possibly be achieved under well-controlled experiment (FIGS. 9A-9C). One tailed student's t-test of paired test were used to calculate the P -value. Scatter plot of T_1 — T_2 diagram (left panels in FIGS. 9A-D) show clustered points which are separated based on its' respectively dilution factors.

As the concentration of met-Hb reduces to less than 0.1%, a larger number of samplings ($n > 5$) were required to improve the sampling probability. Depending on the blood condition (e.g., donor variability, unfresh blood or other anomaly), a time-dependant effect due to a number of confounding factors such as extra— and intracellular water movement across the membrane

altering which shifted the baseline of T_1 and T_2 index (sample C), but retaining the A—ratio. It is also worth noting that, in some cases as the met-Hb concentration were very low ($<0.1\%$) the T_2 parameters were much more stable as compared to T_1 and A—ratio (sample D). Nonetheless, these results combined (either A-ratio and/or T_2 index), MRR technique is at least 3—4 orders

5 much high sensitivity than the photospectrometry system used in this work. Note that, the sensitivity enhancement of MRR technique can achieved by doping met-Hb with natrium fluoride to form fluoromet-Hb, which have much higher relaxivity and is stable towards temperature fluctuation¹. This is however out of the scope of the current study resented here.

Nitrite concentration selection criteria for nitrite—induced oxidation of RBC assays (short-

10 **time 10 min incubation)**

Two selection criteria in deciding the optimal range of nitrite concentration (at 10 min incubation) reflect the high degree of inter-individual variability. The rate limiting factor of this assay is the sample incubation time, which can be reduced by increasing the nitrite concentration to achieve faster turnaround time. Twelve subjects were randomly selected from both the good

15 and bad glycaemic control groups - a range of HbA_{1c} (4.2% to 9.7%). Freshly drawn blood were washed and resuspend into 1x PBS. The blood were then treated with various concentration of sodium nitrite for 10 minutes (FIG. 11A) and the MRR measurements were performed (FIG. 11B). This result (FIGS. 11C and 11D) is used to guide the selection of suitable nitrite concentration which reflects a large degree of inter-individual variability. Box plot indicate the

20 25% and 75% quantiles. The p-values were calculated by using student's t-test for two samples-test of unequal variances. AUC of >0.9 , >0.8 , <0.7 , is consired excellent (dark blue), good (blue) and poor (light blue), respectively.

The induced stress meausrement must be statistically significant different (P -value < 0.05) from both the fully oxy-Hb and met-Hb baselines (FIG. 11C). Secondly, it is desirable to

25 have high degree of inter-individual variability that reflect high resolution as shown by the spread between 25% and 75% quantile box plots. Nitrite concentration in the range of 2mM to 8mM, reflects the bio-homeostatis and satisfied the diagnostic criterion (FIG. 11D). Nonetheless, higher level of differentiation (resolution) between subjects can be achieved by induction with much higher nitrite concentration. However, one should caution against over-stressing the cells

30 as conversion of all RBCs into met-Hb (e.g., 10mM) reveals no information of homeostasis

feedback. In this work, 6mM nitrite was chosen for all the nitrite—induced oxidation assay, unless otherwise mentioned.

Nitrite concentration selection criteria for nitrite—induced oxidation of RBC assays (long-time 36 hrs incubation)

5 The same experiment was repeated on five randomly assigned subjects taken from a range of HbA_{1c} (5.4%—13%) and their responses to various sodium nitrite concentration (0, 5μM, 0.01mM, 0.1mM, 2.0mM, 4.0mM) were recorded (FIGS. 12A-B). In this experiment, the incubation period were increased to 36 hrs instead of 10 min as shown in FIGS. 11A-D. Only 4mM nitrite is needed to induced a complete transition to met-Hb instead of 10mM as shown
10 previously (FIG. 12A). With the longer incubation, the homeostatis feedback range has shifted to 0.5mM—2mM instead of 2mM to 6mM, as shown previously. Therefore, one could use lower nitrite concentration (nM to μM range) can be used if the incubation time is not a limiting factor. Inter-individual variability at low nitrite concentration (μM range) appeared to be much smaller as depicted in log-log plot in FIG. 12B. The p-values were calculated by using student's t-test
15 for two samples-test of unequal variances. AUC of >0.9, >0.8, <0.7, is consired excellent (dark blue), good (blue) and poor (light blue), respectively.

Prolonged effect of *in vitro* exposure to peroxidative stress on RBCs

 Perodixe is a byproducts of oxygen metablolism produces intracellular reactive oxygen species. See, Roche, M., Rondeau, P., Singh, N.R., Tarnus, E. & Bourdon, E. The antioxidant
20 properties of serum albumin. *FEBS letters* **582**, 1783-1787 (2008), which is incorporated by reference in its entirety. The steady state concentration of H₂O₂ in the RBCs is reported to be approximately 0.2nM³, and a dramatic increased has also been shown to be possible under autoxidation⁴. See, Giulivi, C., Hochstein, P. & Davies, K.J. Hydrogen peroxide production by
25 red blood cells. *Free Radical Biology and Medicine* **16**, 123-129 (1994), and Rifkind, J., Zhang, L., Levy, A. & Manoharan, P. The hypoxic stress on erythrocytes associated with superoxide
 formation. *Free Radical Research* **13**, 645-652 (1991), each of which is incorporated by reference in its entirety. The effect on anti-oxidant capacity of RBCs was due to prolonged (day to weeks) *in vitro* exposure to mild concentration of 90nM of hydrogen peroxide (H₂O₂) (FIG. 11).

30 Five subjects with HbA_{1c} (6.1% to 13.8%) were randomly selected for the this experiment and the anti-oxidant capacity of the RBCs were measured by using nitrite—induced

oxidation assay. Freshly drawn blood were washed and resuspended into 1x PBS (Day 0) and divided into two groups; pretreated with H₂O₂ and control (without treatment). In order to understand the total intracellular anti-oxidant properties of RBCs, rather than the whole blood, the serum were removed intentionally. The MRR measurements were performed at Days 1, 6, 13
 5 of post exposure by using nitrite—induced oxidation assay to induce intracellular anti-oxidant capacity of the RBCs. On Day 1 of post—exposure, both the control and peroxide pretreated groups were similar (P -value > 0.05) (FIG. 13A). However, on Day 6 (FIG. 13B), two of the five subjects in H₂O₂ pretreated group (blue) registered a drop in their anti-oxidant capacity as compared to control (red).

10 The same experiment was repeated but with increased hydrogen peroxide concentration of five folds to 500nM. By Day 1 of post-exposure, the dropped in anti-oxidant capacity were registered in all the five subjects (FIG. 13D) and were much more significant as compared to previously observed (FIGS. 13B and 13C). One can translate this *in vitro* observation to understand the *in vivo* cellular damage. While acute infection and impaired ability to reproduce
 15 enzymes in congenital diseases are known to have averse effect, slight elevated stress above normal physiological condition over a prolonged period (e.g., chronic diseases, unhealthy diet) resulting in reduction anti-oxidant capacity. Under normal physiological condition however, cells would be able to constantly repair and renew themselves provided that proper nutrition and diet is within reach.

20 **Low— and High Spin Ferric Hemoglobin in Diabetes Mellitus Subjects**

Oxidative stress is constantly produced endogenously and exogenously. ROS is produced during oxygen metabolism and auto-oxidation, in which met-Hb is spontaneously produced. Most of met-Hb would normally be restored to its' reduced state under normal physiology condition. However, as cells age or under constant pathological stress, the distal histidine of the
 25 hemoglobin would bind to the iron and denatured to form hemichrome. See, Peisach, J., Blumberg, W. & Rachmilewitz, E. The demonstration of ferrihemochrome intermediates in Heinz body formation following the reduction of oxyhemoglobin A by acetylphenylhydrazine. *Biochimica et Biophysica Acta (BBA)-Protein Structure* **393**, 404-418 (1975), and Bernhardt, I. & Ellory, J. Red cell membrane transport in health and disease. (2003), each of which is
 30 incorporated by reference in its entirety. Irreversible hemichrome would eventually aggregate and precipitates on cellular membrane. However, the actual physiological roles of hemichrome

remains controversial. See, Rifkind, J.M., Abugo, O., Levy, A. & Heim, J. Detection, formation, and relevance of hemichromes and hemochromes. *Methods in enzymology* **231**, 449-480 (1993), which is incorporated by reference in its entirety. While hemoglobin promotes most of the biological oxidant processes, oxidized Hb (e.g., HC, met-Hb and free heme) can be the source of stress themselves, and causes damage to RBCs membrane and cytoplasm, and functional impairments.

FIG. 10A shows the T_1 - T_2 diagram of RBCs exposed to salicylic (round) and control (square) in *in vitro* environment at different time point (1, 5, 10, 20, 60) minutes. FIG. 10B shows the corresponding A—ratio in time evolution. FIG. 10C shows the T_1 - T_2 diagram for RBCs of non DM (square) and DM subjects (round) exposed to 0.125M sodium salicylic (10 min). FIG. 10D shows the corresponding A—ratio.

Hemichrome (HC) can be induced in *in-vitro* environment by incubating sodium salicylic with freshly collected blood (FIG. 3A). HC is poorly resolved with a broad valley between 540—580 nm in spectrophotometer. See, Della Longa, S., *et al.* Iron site structure of two irreversible hemichromes from human hemoglobin, untreated and oxidized to sulfoxide at MetD6 (55) beta. *Biochimica et biophysica acta* **1294**, 72-76 (1996), which is incorporated by reference in its entirety. In contrast, the MRR measurements indicate that high-spin met-Hb (T_2 =98ms, T_1 =198ms, A=2.02) and low-spin hemichrome (T_2 =113ms, T_1 =587ms, A=5.19) have unique relaxation times (and hence, the A—ratio). Although HC has similar ferric oxidation state as met-Hb, is in much lower spin-state with only 3 unpaired electrons (FIG. 1E). As distal histidine of the hemoglobin bound to the iron on the sixth coordinate, the T_1 for HC is therefore significantly longer than T_1 of met-Hb, which has water proton on the sixth coordinate, and therefore subject to different Brownian fluctuation. Thus, despite sharing the ferric-oxidation and in paramagnetic states, both HC and met-Hb is fully resolved as reflected in the state-diagram (FIG. 3B).

Peroxide concentration selection criteria for peroxide—induced oxidation of HSA assays.

Two selection criteria can be used for an optimal range of peroxide concentration. Eight subjects were randomly selected from both the good and bad glycaemic control groups. Firstly, the induced stress requires to be statistically significant different (P -value < 0.5 and AUC > 0.8) from both the non-oxidized HSA and oxidized HSA baselines. Secondly, it is desirable to have large degree of inter-individual variability, as shown by the spread between 25% and 75%

quantile box plots (FIGS. 14A-E). The 0.3% to 0.4% concentration range fit the selection. In these examples, 0.3% peroxide has been chosen unless mentioned otherwise.

***In vitro* glycation of plasma serum and Oxidative status**

In order to investigate the effect of glucose has on the plasma serum, *in vitro* glycation was performed by adding glucose (control, 10mM and 100mM) to freshly drawn plasma on three different subjects (Day 0) (Methods Online). MRR measurements, photospectrometry absorbance, and glucose in plasma were recorded simultaneously on day six after incubation. The initial plasma glucose readings were (5.6, 7.1, 7.3) mmol/L for subject A, B and C, respectively.

On Day 6, the T_1 and T_2 relaxations showed marked reduction as the amount of glucose increases on all the three subjects (FIGS. 15A and 15B). T_2 relaxation, however reduces much faster than T_1 relaxation (arrows in FIG. 15A), hence the increment of $A_{\text{baseline}}\text{---ratio}$ (FIG. 15C) which were due to the effect of glycation. This corresponds well with the cross sectional study (*in vivo* measurements shown in FIG. 5A, and FIGS. 6A-6C). Peroxidative assay with 0.3% hydrogen peroxide reveals that the plasma serum has much lower antioxidant capacity as a function of glycaemic level (FIG. 15C; bottom three boxes). As more serum is oxidized, the T_1 relaxation time reduces much faster than T_2 relaxation time, and hence the reduction in $A_{\text{peroxidative}}\text{---ratio}$ (FIG. 15C). Despite the fact that both glycation and glycooxidation shared the same effect of T_1 and T_2 relaxation times reduction, the $A_{\text{peroxidative}}\text{---ratio}$ (bottom three boxes) and $A_{\text{baseline}}\text{---ratio}$ (top three boxes) were orthogonal parameters (FIG. 15C), making it possible to differentiate between the two effects.

In vitro study here allows one to study the effect of glucose exposure quantitatively on the same subject to mimic the longitudinal study in actual *in vivo* subject. Furthermore, the effect of *in vitro* glycation and glycooxidation were similar as revealed in the cross sectional *in vivo* study (FIGS. 5 and 6). It is also worth noting that MRR measurements of 5.5mM of glucose with and without 3% H_2O_2 mixture (10% v/v) were ($T_2=2290$, $T_1=2441$, $A=1.07$) and ($T_2=2337$, $T_1=2461$, $A=1.05$), respectively. This implied that either H_2O_2 does not interact directly with glucose (no physical and color changes or precipitate were observed) or did not alter the relaxation states substantially.

Clinical *In vivo* Diabetes Subject: Correlation of Glycaemic levels and MRR Oxidative Status

The relationship between peroxidative susceptibility (normalized A—ratio) and glycaemic levels, for both the HbA_{1c} and fructosamine, are investigated. MRR measurements were performed on the plasma serum using peroxidative assay. The peroxidative susceptibility was also found to be positively correlated to glycaemic levels, both the HbA_{1c} (FIG. 16A) and fructosamine level (FIG. 16B). As expected the correlation between HbA_{1c} and fructosamine were high ($R^2 > 0.83$), similar to the work reported by Hindle (FIG. 16C). See, Hindle, E., Rostron, G., Clark, S. & Gatt, J. Serum fructosamine and glycated haemoglobin measurements in diabetic control. *Archives of disease in childhood* **61**, 113-117 (1986), which is incorporated by reference in its entirety. The degree of glycosylation of hemoglobin (HbA_{1c}) and serum proteins (fructosamine) has been correlated with indices of glycaemia. See, Johnson, R.N., Metcalf, P.A. & Baker, J.R. Fructosamine: a new approach to the estimation of serum glycosylprotein. An index of diabetic control. *Clinica Chimica Acta* **127**, 87-95 (1983), and Johnson, R.N., Metcalf, P.A. & Baker, J.R. Relationship between albumin and fructosamine concentration in diabetic and non-diabetic sera. *Clinica chimica acta* **164**, 151-162 (1987), each of which is incorporated by reference in its entirety.

Other embodiments are within the scope of the following claims.

WHAT IS CLAIMED IS:

1. A method of monitoring a disease status comprising:
obtaining a sample from a subject,
5 measuring a longitudinal relaxation time and a transverse relaxation time in the sample; and
assessing a redox state of the sample from the longitudinal relaxation time and the transverse
relaxation time of the sample.
2. The method of claim 1, wherein assessing the redox state includes:
10 plotting a magnetic state diagram of a longitudinal relaxation time and a transverse relaxation
time; and
interpreting the state of the sample based on the location of the sample in the diagram.
3. The method of claim 1, wherein assessing the redox state includes:
15 calculating a ratio of longitudinal relaxation time to transverse relaxation time of the sample; and
comparing the ratio with a predetermined ratio of a reference sample.
4. The method of claim 1, wherein measuring the longitudinal relaxation time and the
transverse relaxation time comprises:
20 inserting the sample within a detection coil of a magnetic resonance relaxometry device.
5. The method of claim 4, wherein the device comprises:
a radio-frequency spectrometer comprising at least one field- programmable gate array chip;
a power amplifier electrically connected with the radio-frequency spectrometer and amplifying
25 an electrical output of the radio-frequency spectrometer, thereby producing an amplified
electrical signal comprising between about 0.1 Watts and about 10 Watts power;
a duplexer configured to isolate the radio-frequency spectrometer from the amplified electrical
signal during a receiving mode of the device; a radio-frequency detection probe configured to
transmit radio- frequency electromagnetic radiation to excite nuclei under resonance during a
30 transmission mode of the device, the radio-frequency detection probe comprising a detection coil
comprising an inner diameter of less than about 1 millimeter; and

at least one magnet supplying an external magnetic field to a detection region of the radio-frequency detection probe, the external magnetic field being less than about 3 Tesla.

6. The method of claim 4, wherein the device comprises an NMR spectroscopy using higher
5 external magnetic field higher than about 3 Tesla.

7. The method of claim 1, wherein the sample is a blood sample.

8. The method of claim 6, wherein the blood sample is plasma or red blood cells.

9. The method of claim 1, wherein the disease is diabetes mellitus.

10. The method of claim 1, wherein the redox state is a level of oxidative stress.

11. The method of claim 1, wherein the redox state is a level of oxidative stress of
hemoglobin.

12. The method of claim 1, wherein the redox state is a level of nitrosative stress.

13. The method of claim 1, wherein the redox state is a level of nitrosative stress of
hemoglobin.

14. A method of identifying a risk for diabetes mellitus in a patient comprising:
measuring a longitudinal relaxation time and a transverse relaxation time using a
magnetic resonance relaxometry device in a blood sample of the patient; and
assigning a risk level to a subject based on a ratio of the longitudinal relaxation time and
the transverse relaxation time.

15. The method of claim 14, wherein the device comprises:
a radio-frequency spectrometer comprising at least one field- programmable gate array chip;

a power amplifier electrically connected with the radio-frequency spectrometer and amplifying an electrical output of the radio-frequency spectrometer, thereby producing an amplified electrical signal comprising between about 0.1 Watts and about 10 Watts power;
a duplexer configured to isolate the radio-frequency spectrometer from the amplified electrical
5 signal during a receiving mode of the device; a radio-frequency detection probe configured to transmit radio- frequency electromagnetic radiation to excite nuclei under resonance during a transmission mode of the device, the radio-frequency detection probe comprising a detection coil comprising an inner diameter of less than about 1 millimeter; and
at least one magnet supplying an external magnetic field to a detection region of the radio-
10 frequency detection probe, the external magnetic field being less than about 3 Tesla.

16. The method of claim 14, wherein the magnetic resonance relaxometry device comprises an NMR spectroscopy using higher external magnetic field higher than about 3 Tesla.

15 17. A method of assessing a redox state of a sample comprising:
plotting a magnetic state diagram of a longitudinal relaxation time and a transverse relaxation time, wherein the longitudinal relaxation time and the transverse relaxation time are measured using a magnetic resonance relaxometry device; and
interpreting the state of the sample based on the location of the sample in the diagram.

20 18. The method of claim 17, wherein the redox state is a level of oxidative stress.

19. The method of claim 17, wherein the redox state is a level of oxidative stress of hemoglobin.

25 20. The method of claim 17, wherein the redox state is a level of nitrosative stress.

21. The method of claim 17, wherein the redox state is a level of nitrosative stress of hemoglobin.

30 22. The method of claim 17, wherein the sample is a blood sample.

23. The method of claim 22, wherein the blood sample is plasma or red blood cells.

24. The method of claim 17, wherein the magnetic resonance relaxometry device comprises:
5 a radio-frequency spectrometer comprising at least one field- programmable gate array chip;
a power amplifier electrically connected with the radio-frequency spectrometer and amplifying
an electrical output of the radio-frequency spectrometer, thereby producing an amplified
electrical signal comprising between about 0.1 Watts and about 10 Watts power;
a duplexer configured to isolate the radio-frequency spectrometer from the amplified electrical
10 signal during a receiving mode of the device; a radio-frequency detection probe configured to
transmit radio- frequency electromagnetic radiation to excite nuclei under resonance during a
transmission mode of the device, the radio-frequency detection probe comprising a detection coil
comprising an inner diameter of less than about 1 millimeter; and
at least one magnet supplying an external magnetic field to a detection region of the radio-
15 frequency detection probe, the external magnetic field being less than about 3 Tesla.

25. The method of claim 17, wherein the magnetic resonance relaxometry device comprises
an NMR spectroscopy using higher external magnetic field higher than about 3 Tesla.

20 26. A method of assessing a redox state of a sample comprising:
calculating a ratio of longitudinal relaxation time to transverse relaxation time of the sample,
wherein the longitudinal relaxation time and the transverse relaxation time are measured using a
magnetic resonance relaxometry device; and
comparing the ratio with a predetermined ratio of a reference sample.

25 27. The method of claim 26, wherein the redox state is a level of oxidative stress.

28. The method of claim 26, wherein the redox state is a level of oxidative stress of
hemoglobin.

30 29. The method of claim 26, wherein the redox state is a level of nitrosative stress.

30. The method of claim 26, wherein the redox state is a level of nitrosative stress of hemoglobin.

5 31. The method of claim 26, wherein the sample is a blood sample.

32. The method of claim 31, wherein the blood sample is plasma or red blood cells.

33. The method of claim 26, wherein the magnetic resonance relaxometry device comprises:
10 a radio-frequency spectrometer comprising at least one field- programmable gate array chip;
a power amplifier electrically connected with the radio-frequency spectrometer and amplifying
an electrical output of the radio-frequency spectrometer, thereby producing an amplified
electrical signal comprising between about 0.1 Watts and about 10 Watts power;
a duplexer configured to isolate the radio-frequency spectrometer from the amplified electrical
15 signal during a receiving mode of the device; a radio-frequency detection probe configured to
transmit radio- frequency electromagnetic radiation to excite nuclei under resonance during a
transmission mode of the device, the radio-frequency detection probe comprising a detection coil
comprising an inner diameter of less than about 1 millimeter; and
at least one magnet supplying an external magnetic field to a detection region of the radio-
20 frequency detection probe, the external magnetic field being less than about 3 Tesla.

34. The method of claim 26, wherein the magnetic resonance relaxometry device comprises
an NMR spectroscopy using higher external magnetic field higher than about 3 Tesla.

25 35. A method of monitoring a hemoglobin state using a magnetic state diagram,
wherein the diagram is represented by a two-dimensional plot of a longitudinal relaxation
time and a transverse relaxation time.

36. A magnetic state diagram for assessing redox state of a sample comprising:
30 a two-dimensional plot of a longitudinal relaxation time and a transverse relaxation time
of the sample.

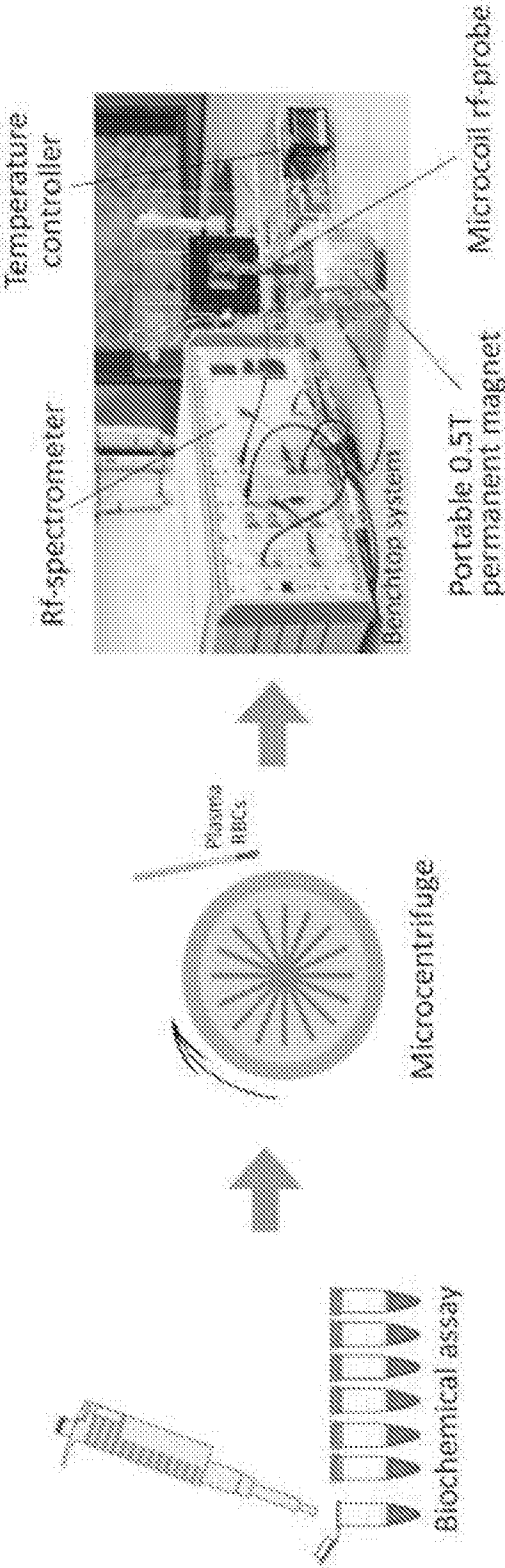


FIG. 1A

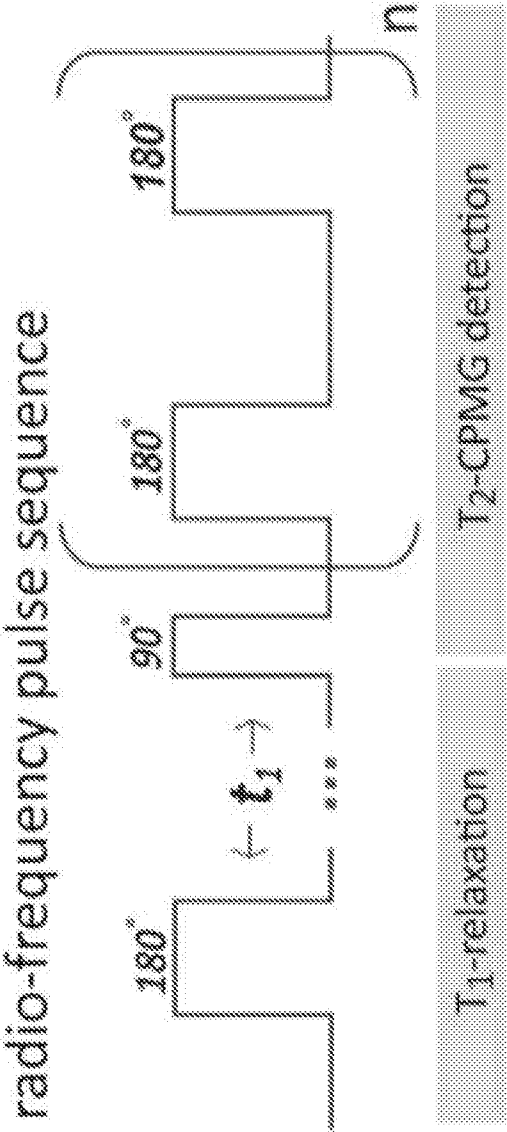


FIG. 1B

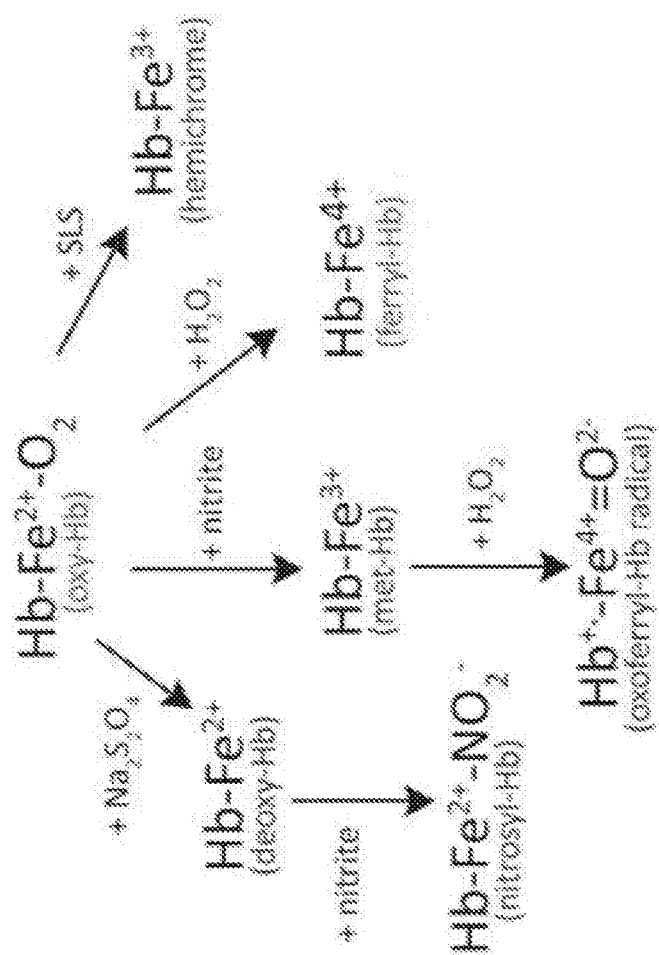


FIG. 1C

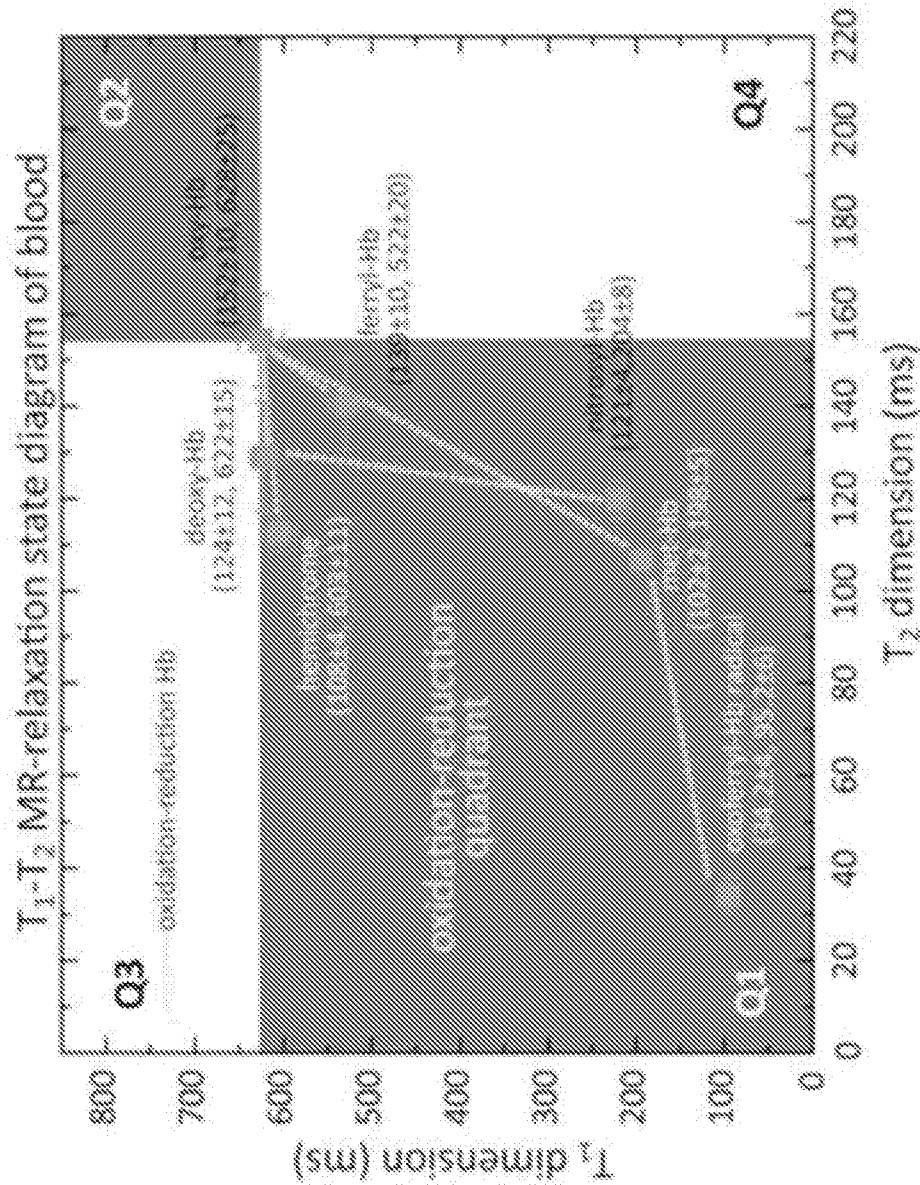


FIG. 1D

Hemoglobin	Oxidation State	Number of unpaired electrons	A-ratio	Magnetic States
Oxy-Hb	Fe(II)	nil	4.13	Diamagnetic
Deoxy-Hb	Fe(II)	4	5.02	Paramagnetic
Nitrosyl-Hb	Fe(II)	?	1.69	Paramagnetic
Hemichrome	Fe(III)	3	5.58	Paramagnetic
Met-Hb	Fe(III)	5	1.94	Paramagnetic
Feryl-Hb	Fe(IV)	nil	3.76	Diamagnetic
Oxoferryl-Hb	Fe(IV)	1(globin-based)	2.78	Paramagnetic

FIG. 1E

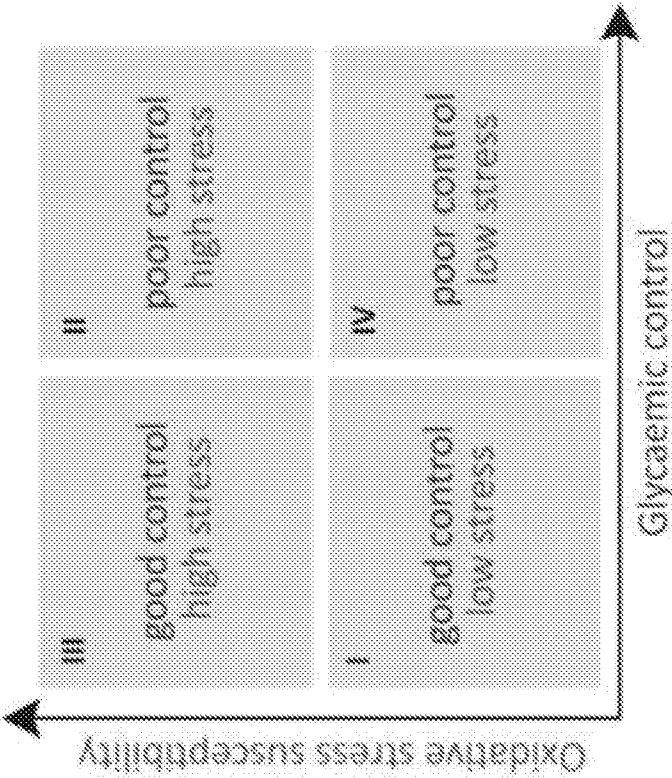


FIG. 1F

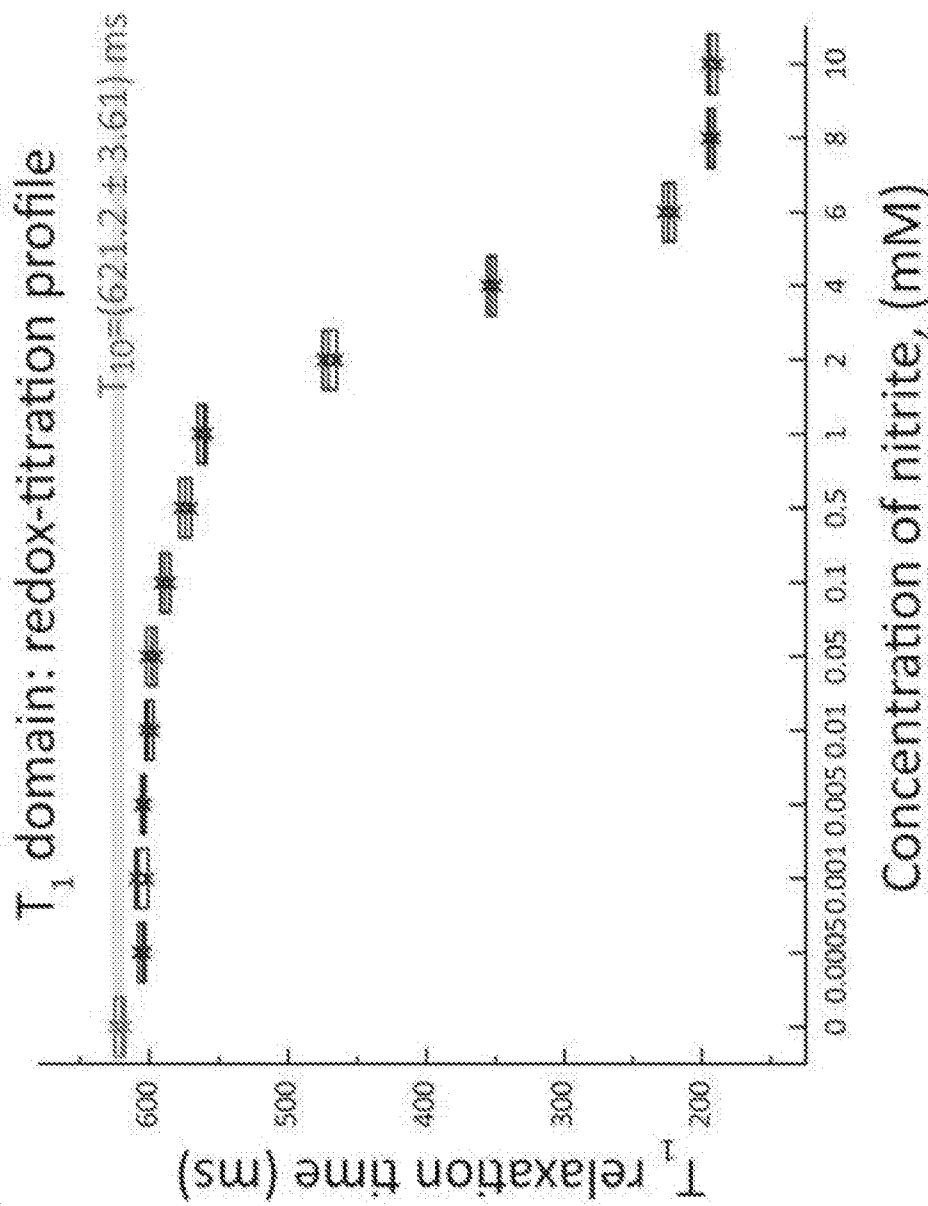


FIG. 2A

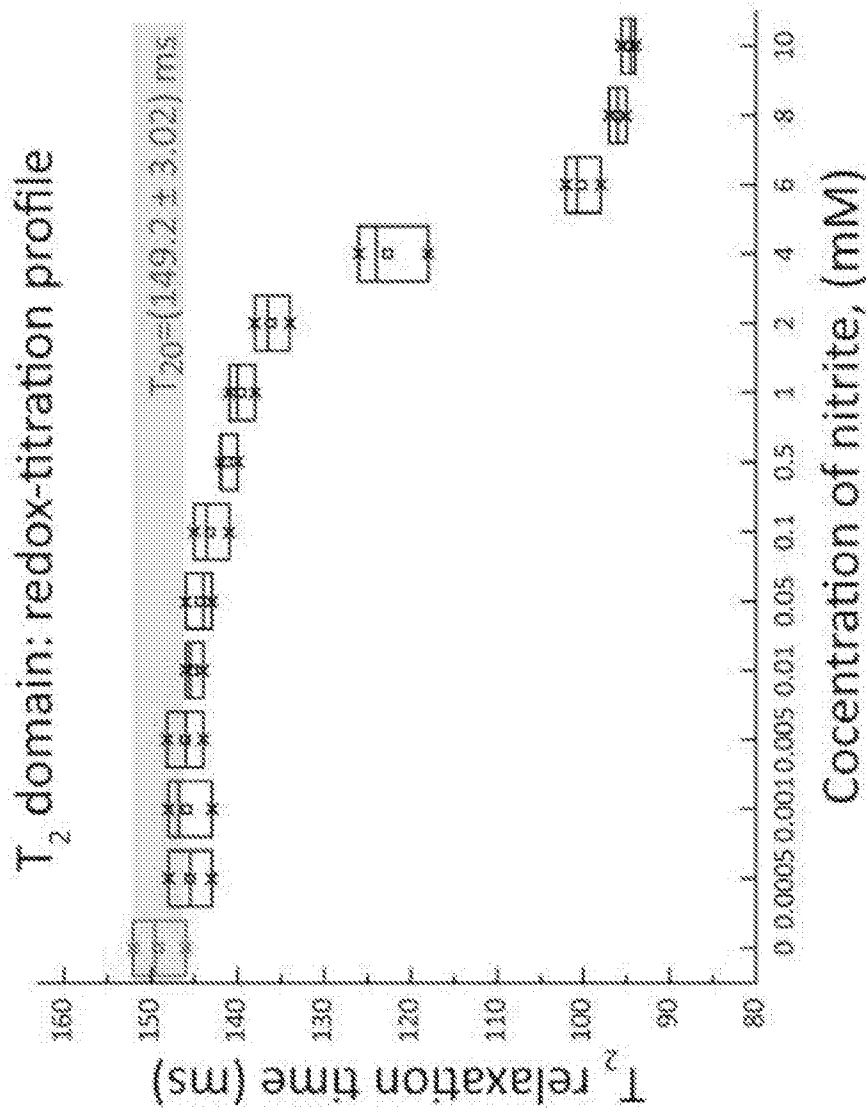


FIG. 2B

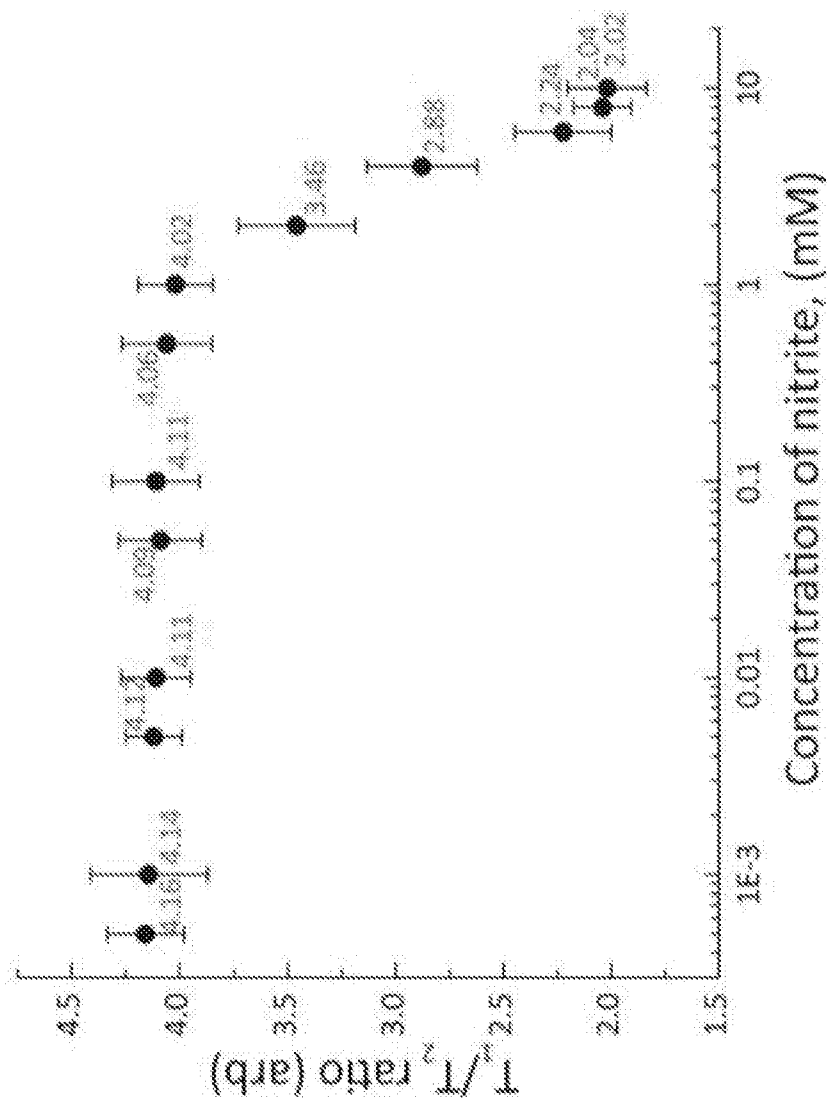


FIG. 2C

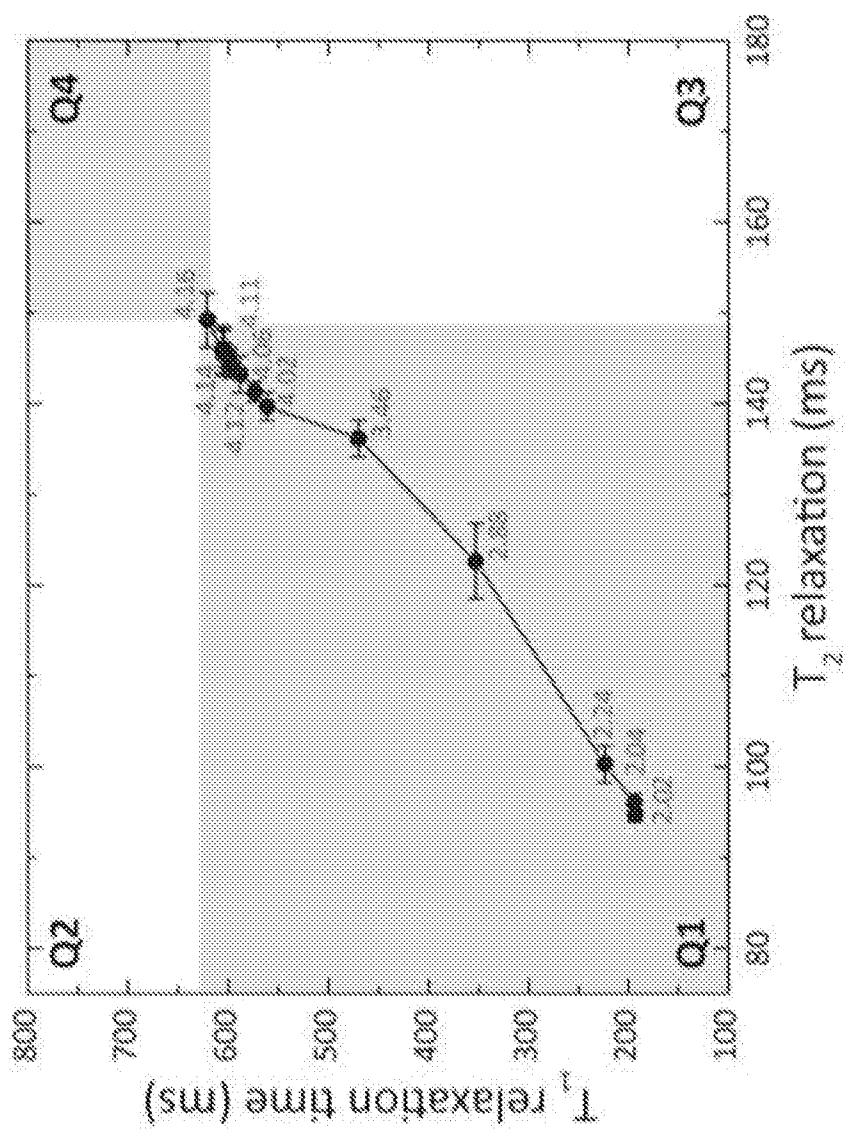


FIG. 2D

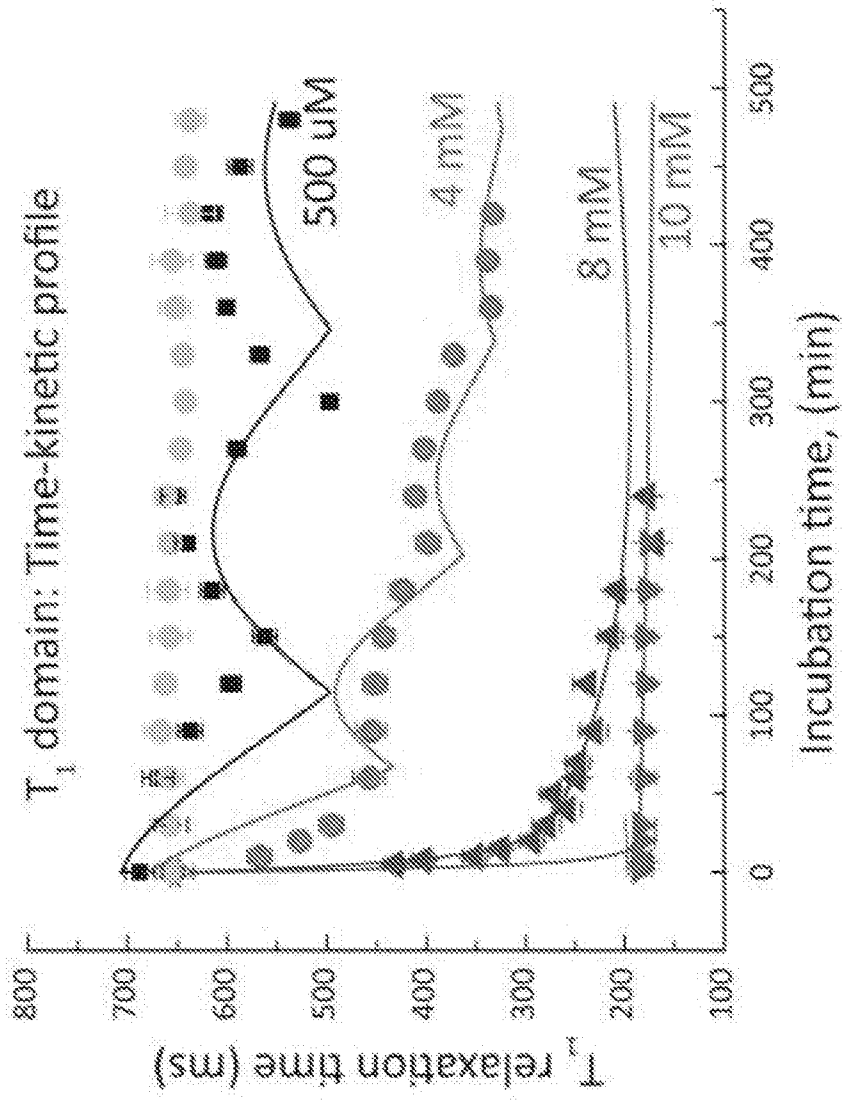


FIG. 2E

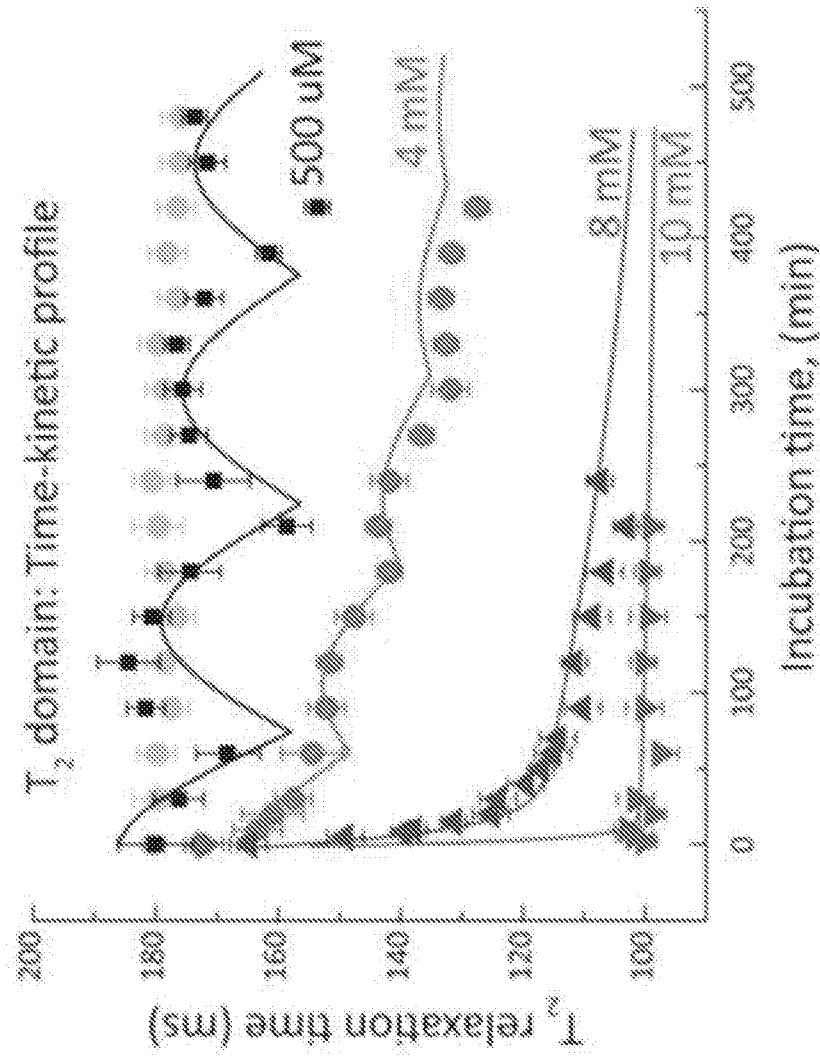


FIG. 2F

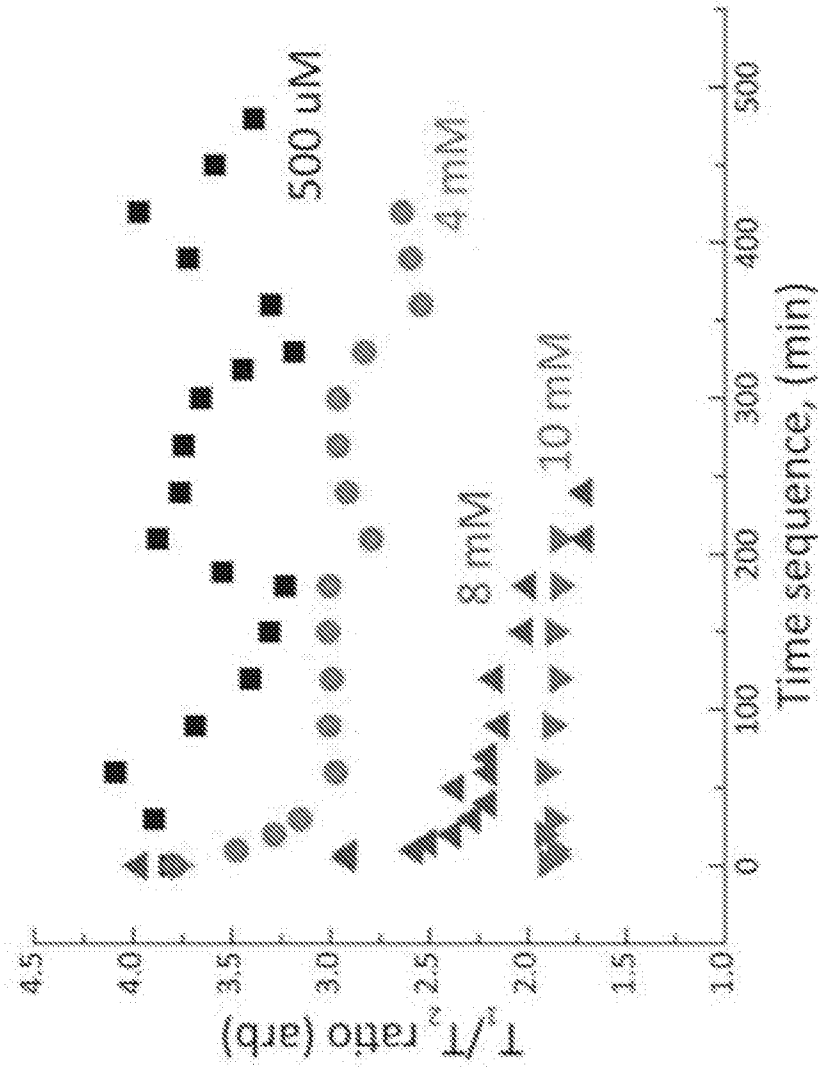


FIG. 2G

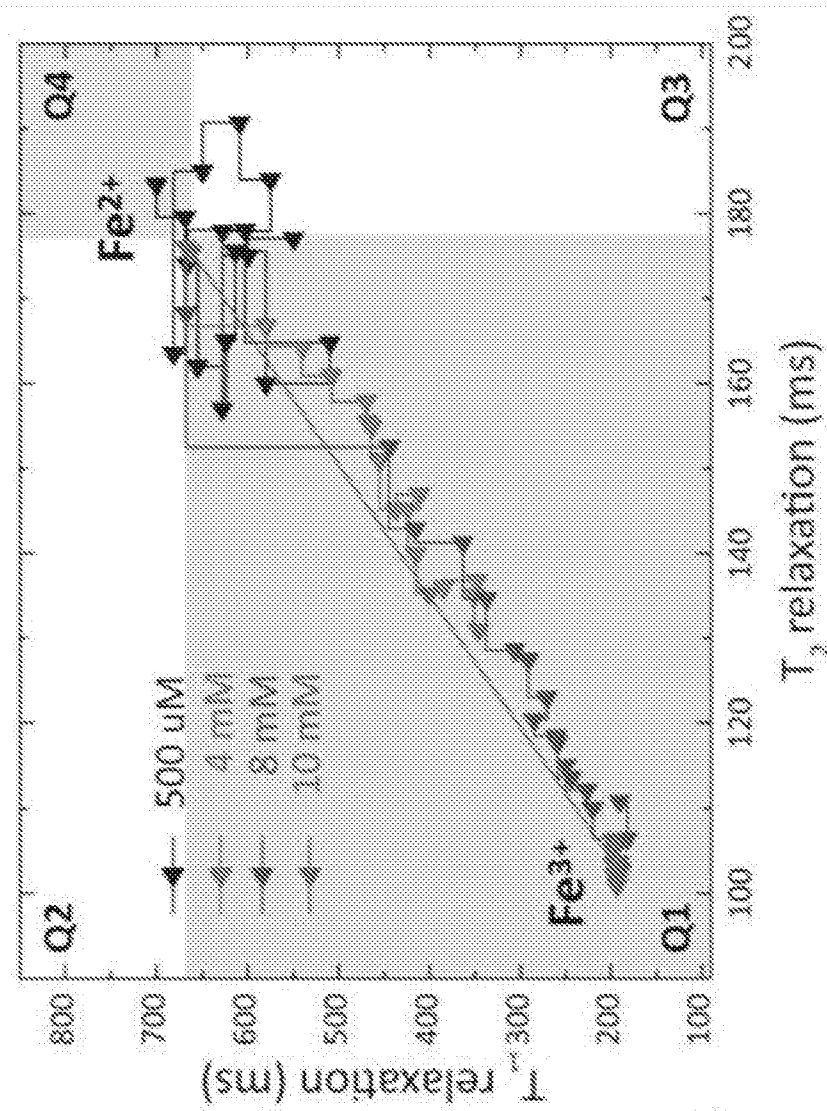


FIG. 2H

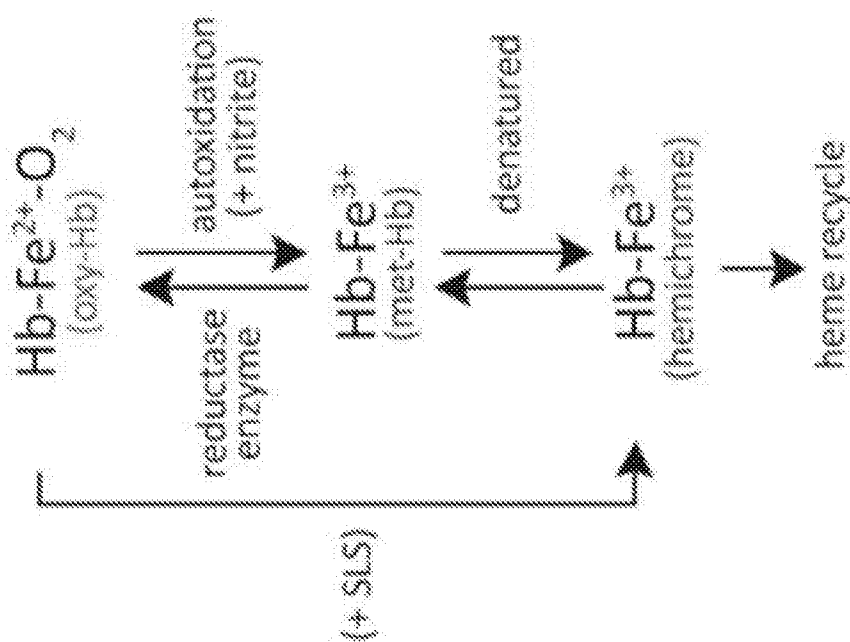


FIG. 3A

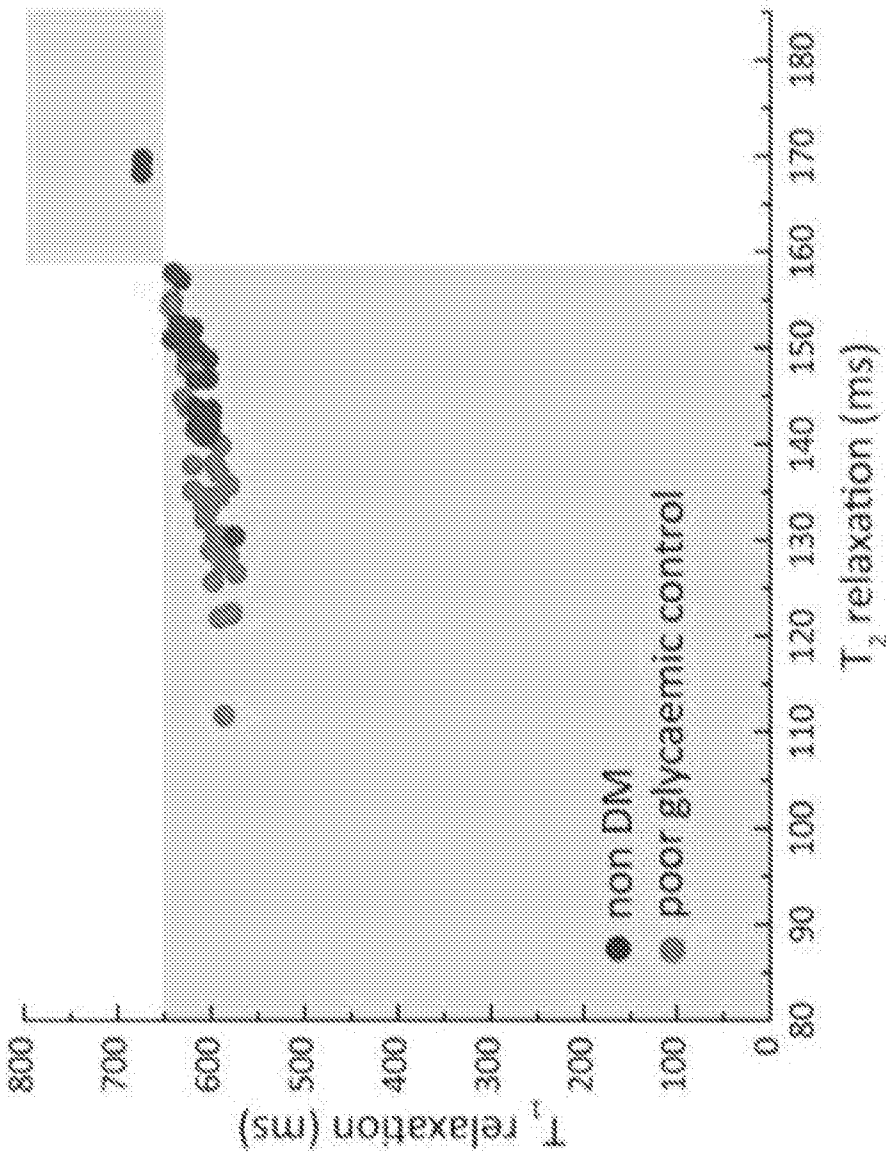


FIG. 3B

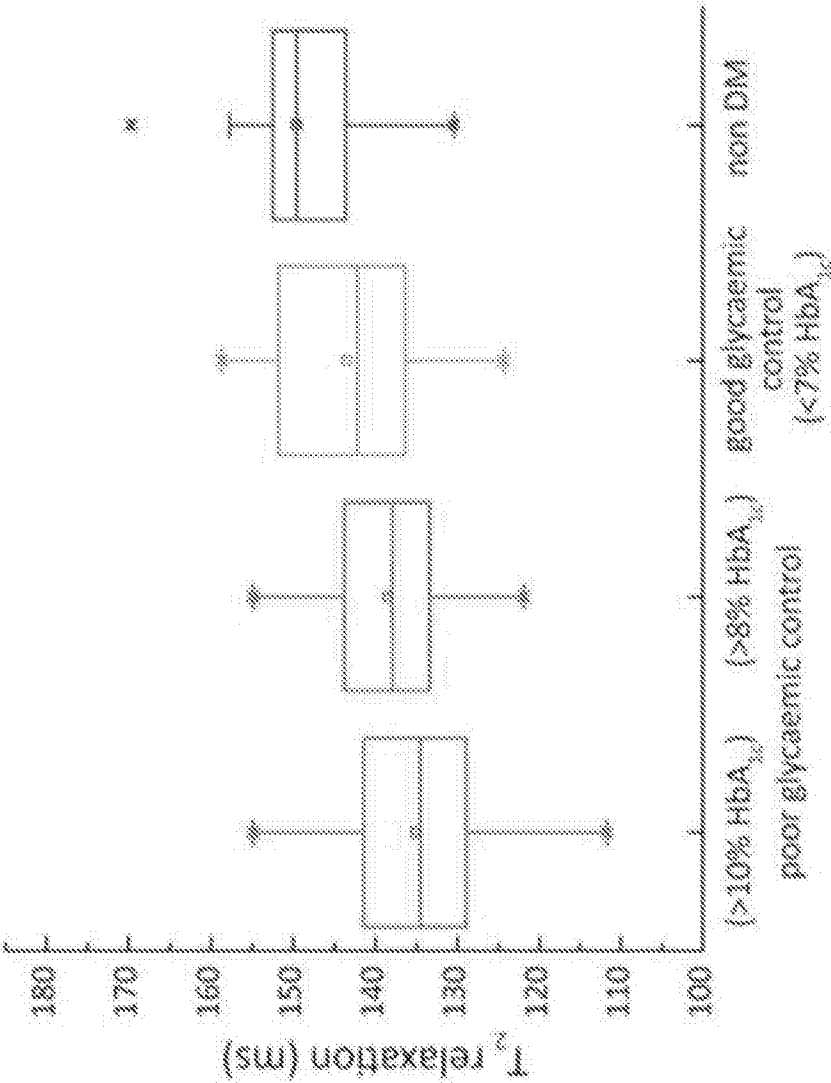


FIG. 3C

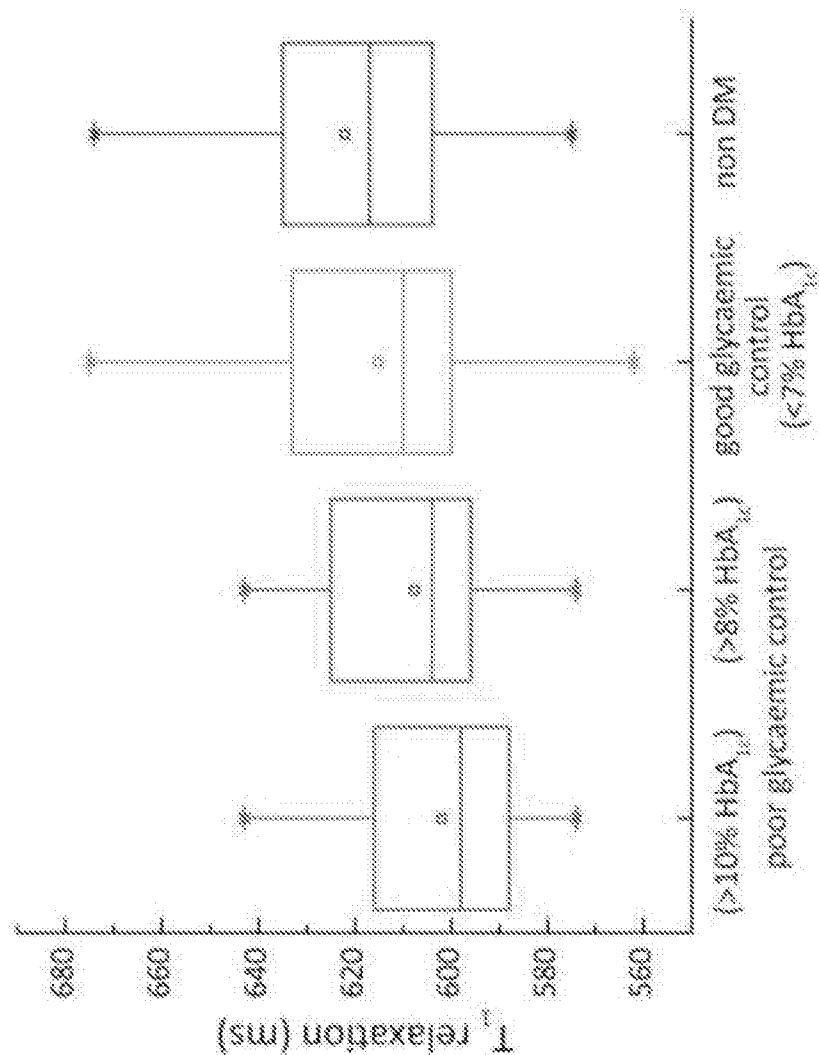


FIG. 3D

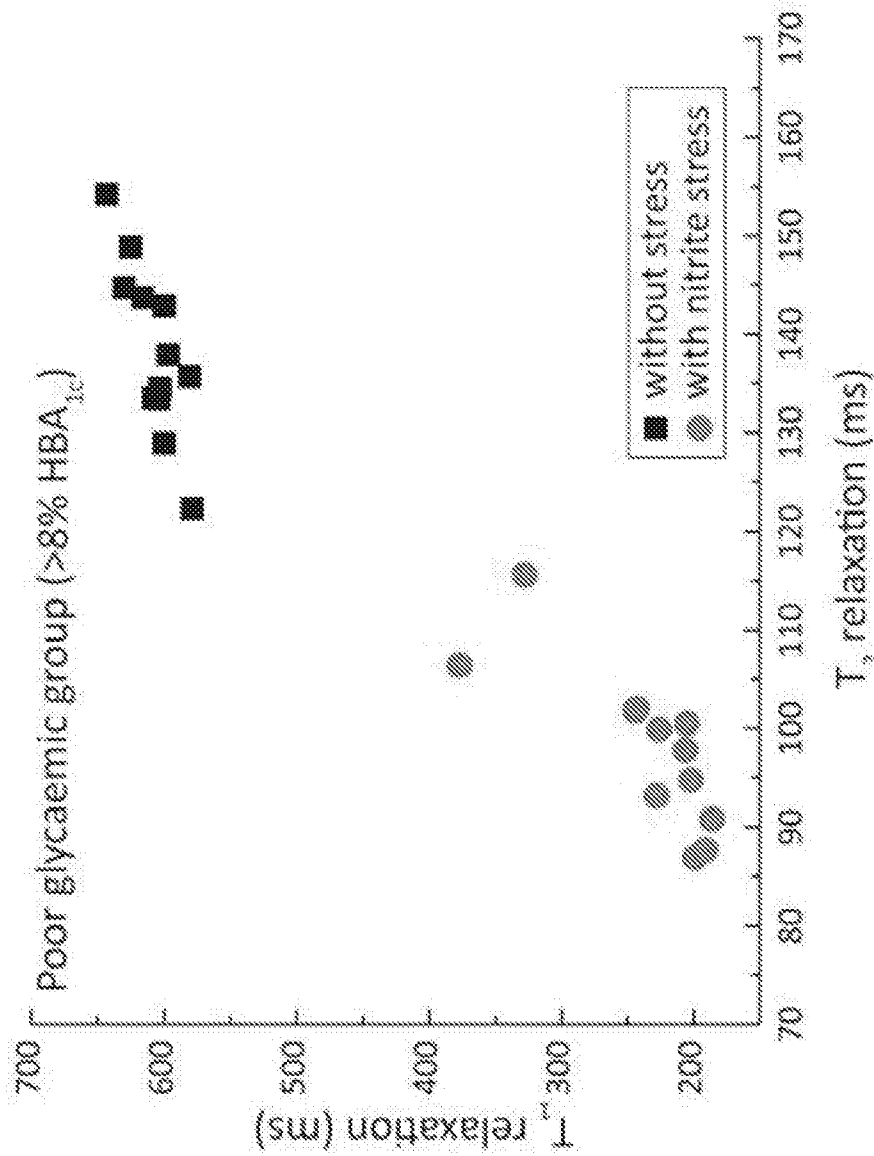


FIG. 4A

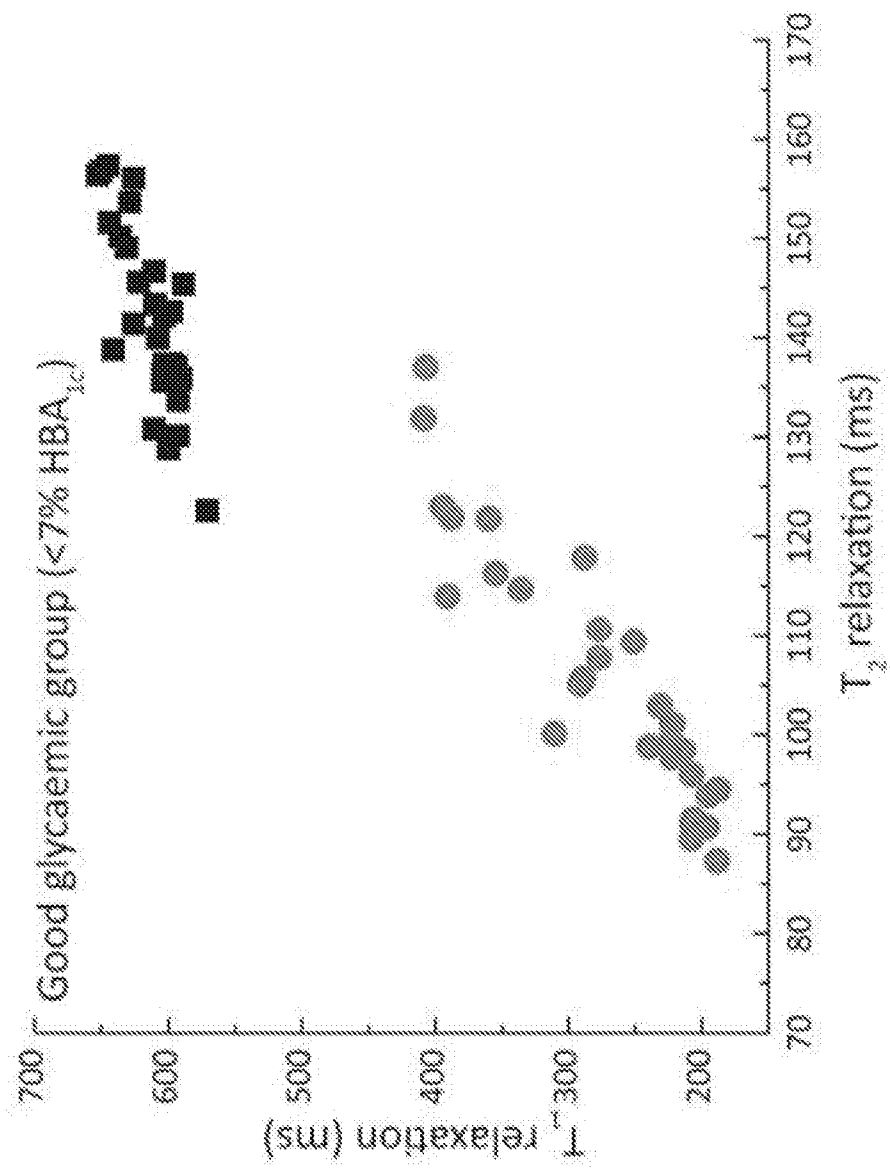


FIG. 4B

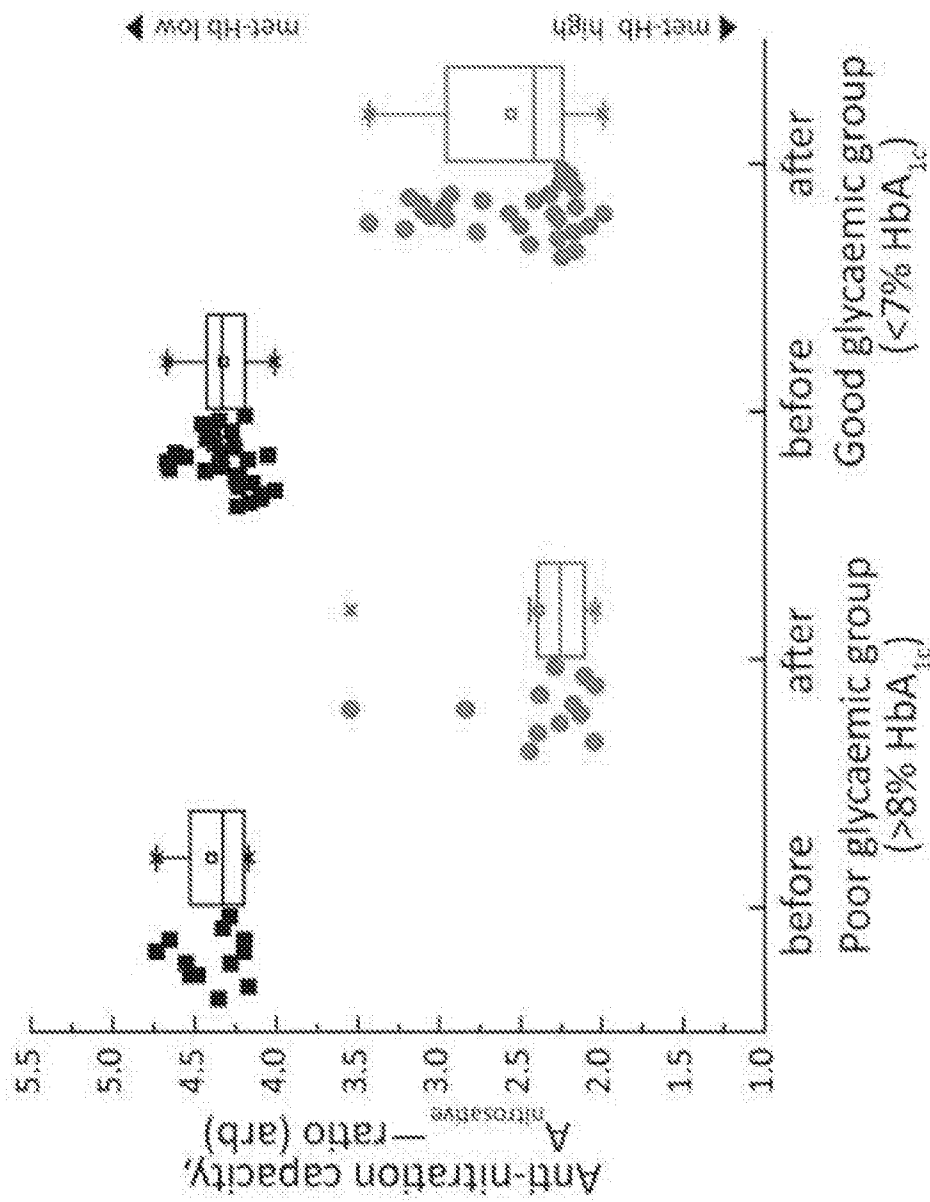


FIG. 4C

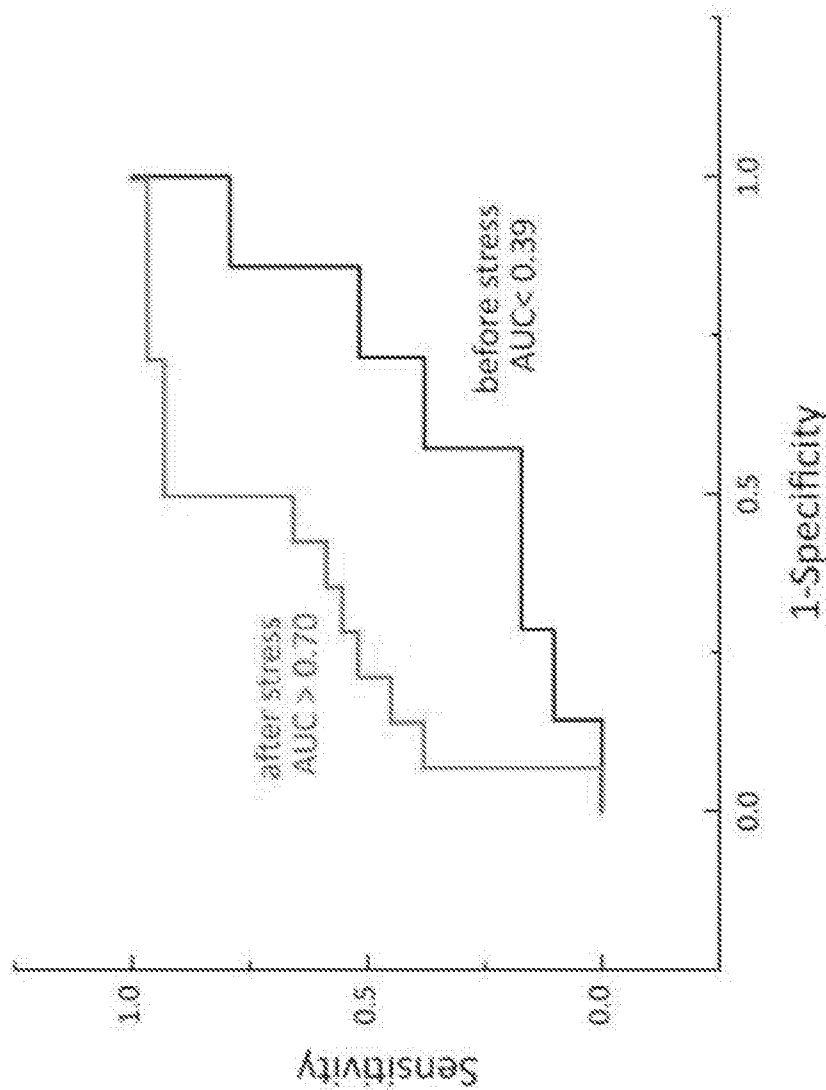


FIG. 4D

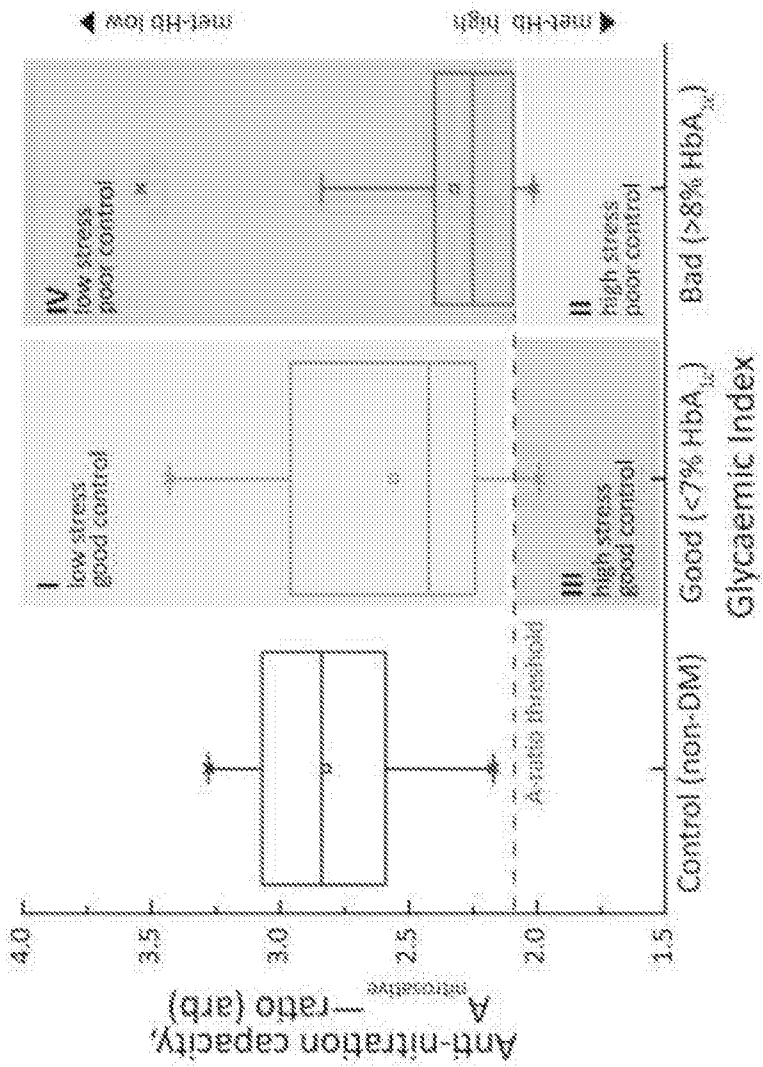


FIG. 4E

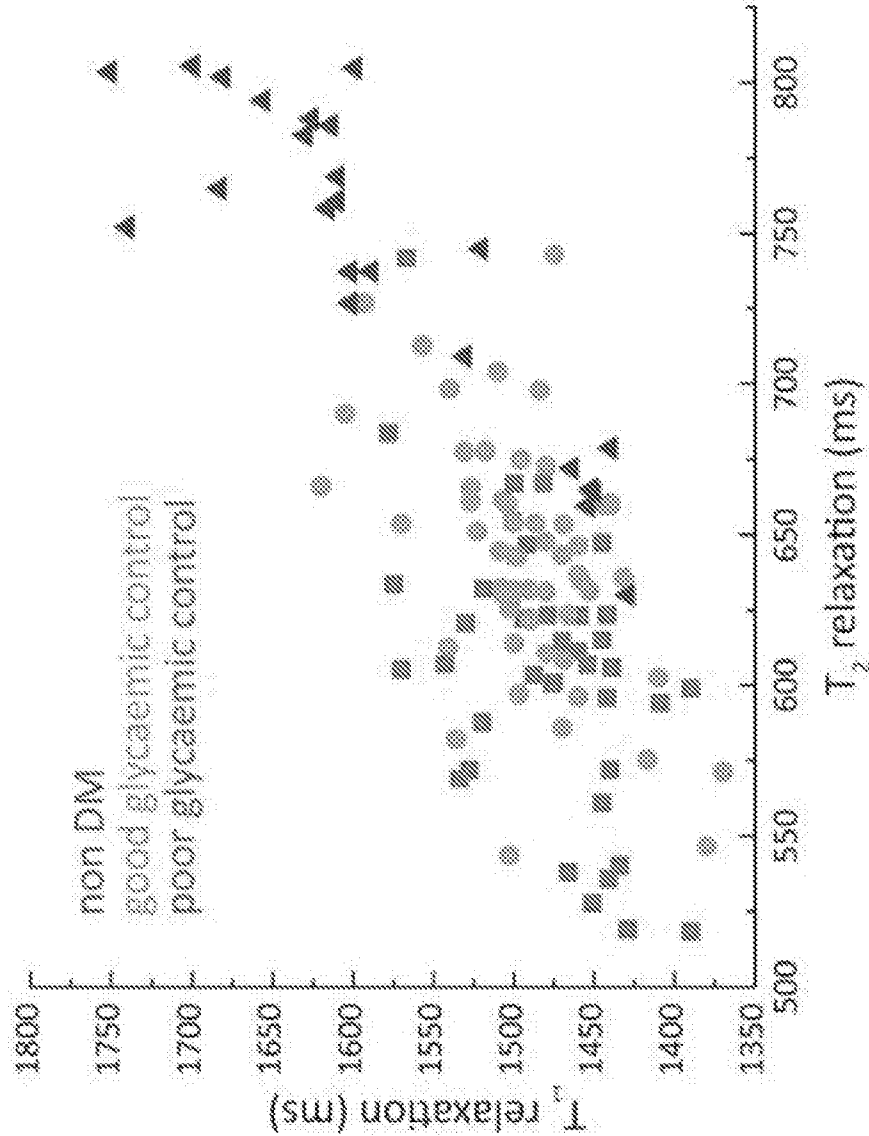


FIG. 5A

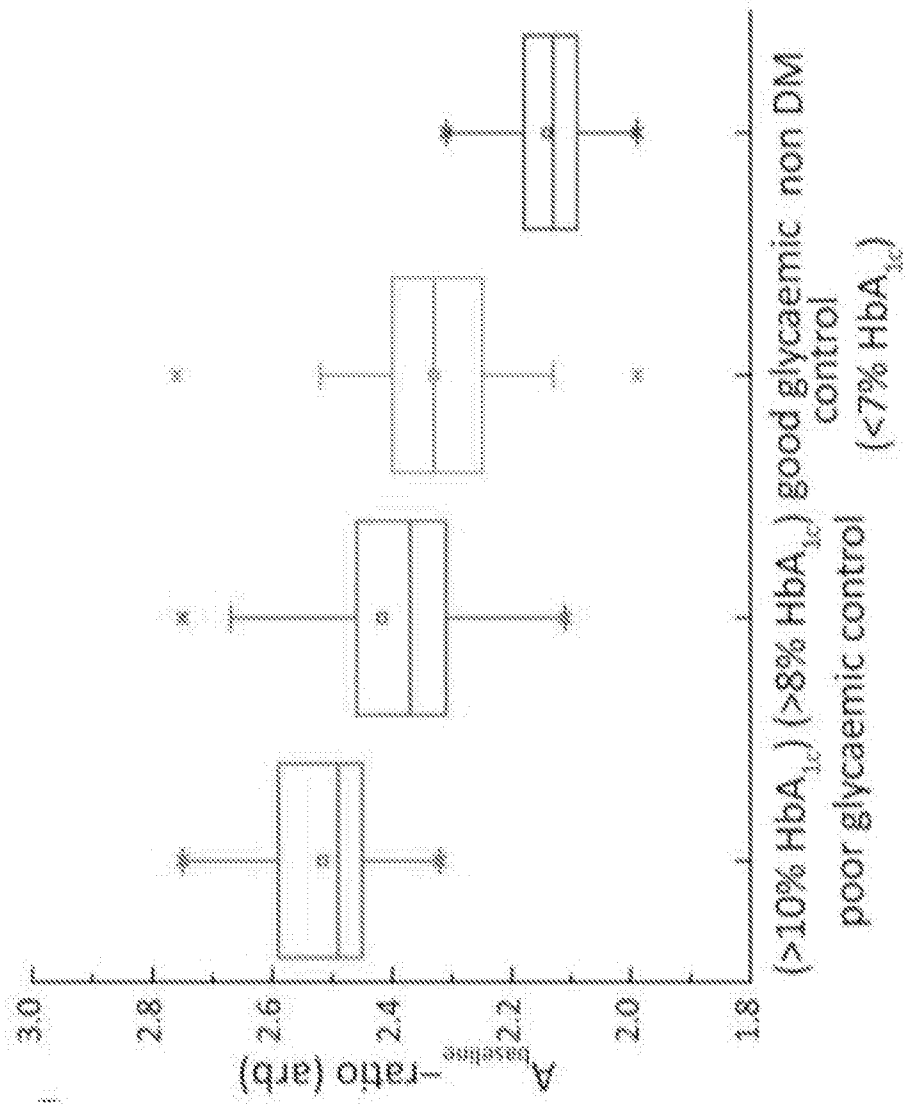


FIG. 5B

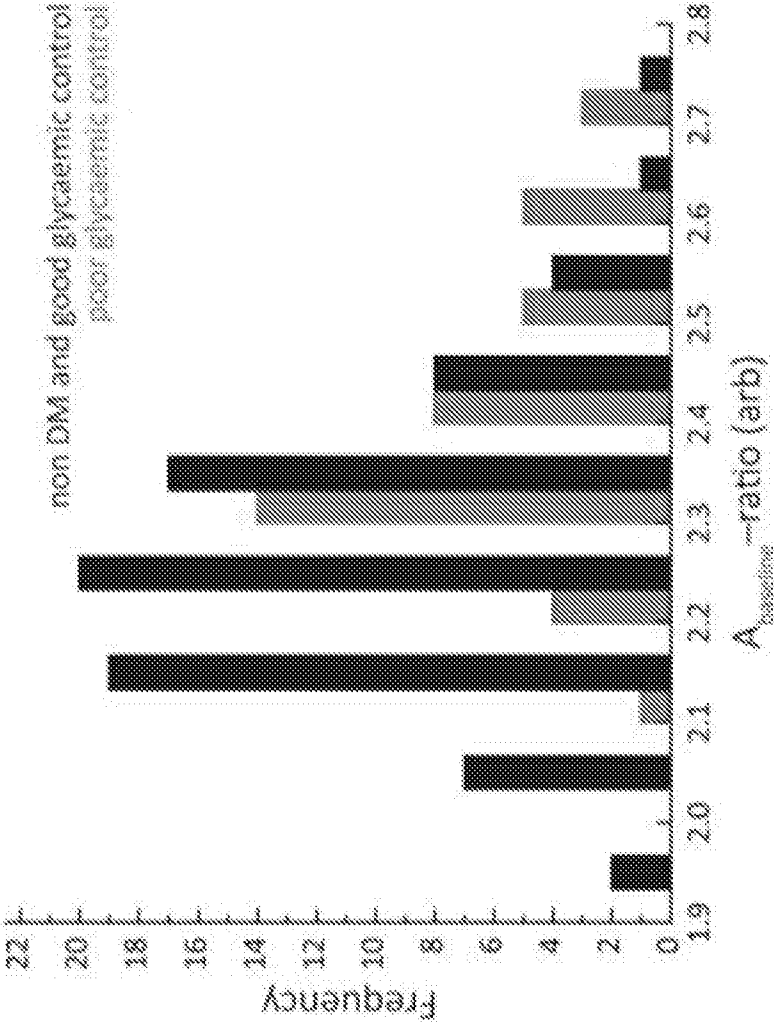


FIG. 5C

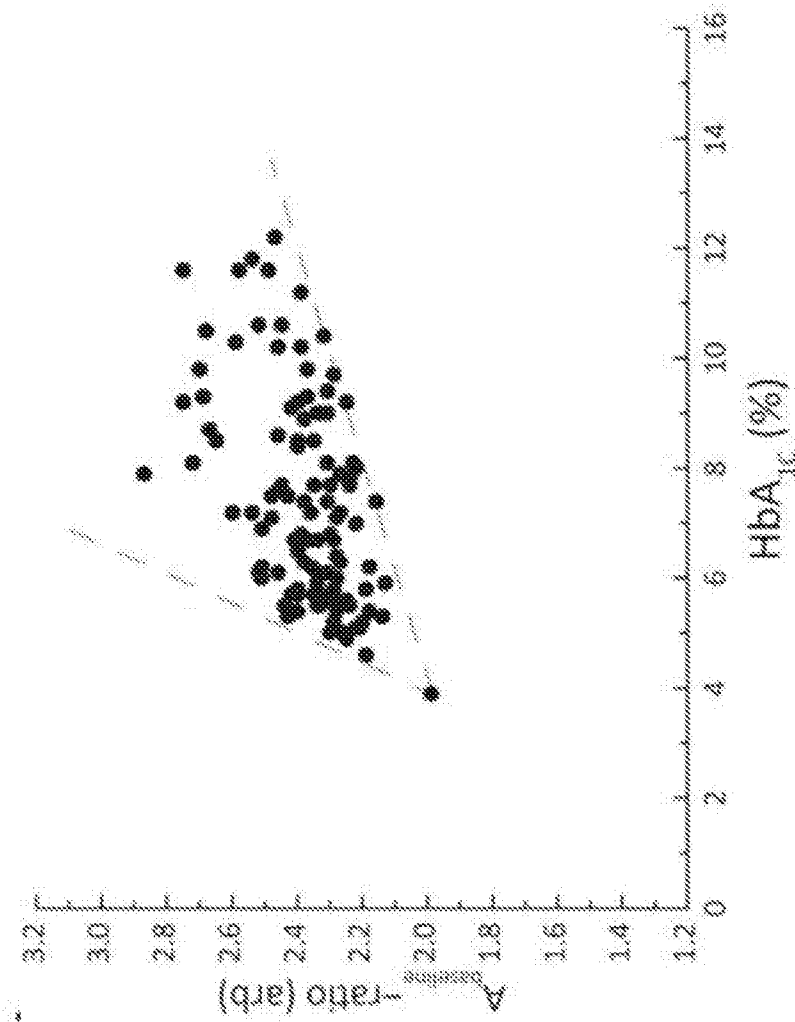


FIG. 5D

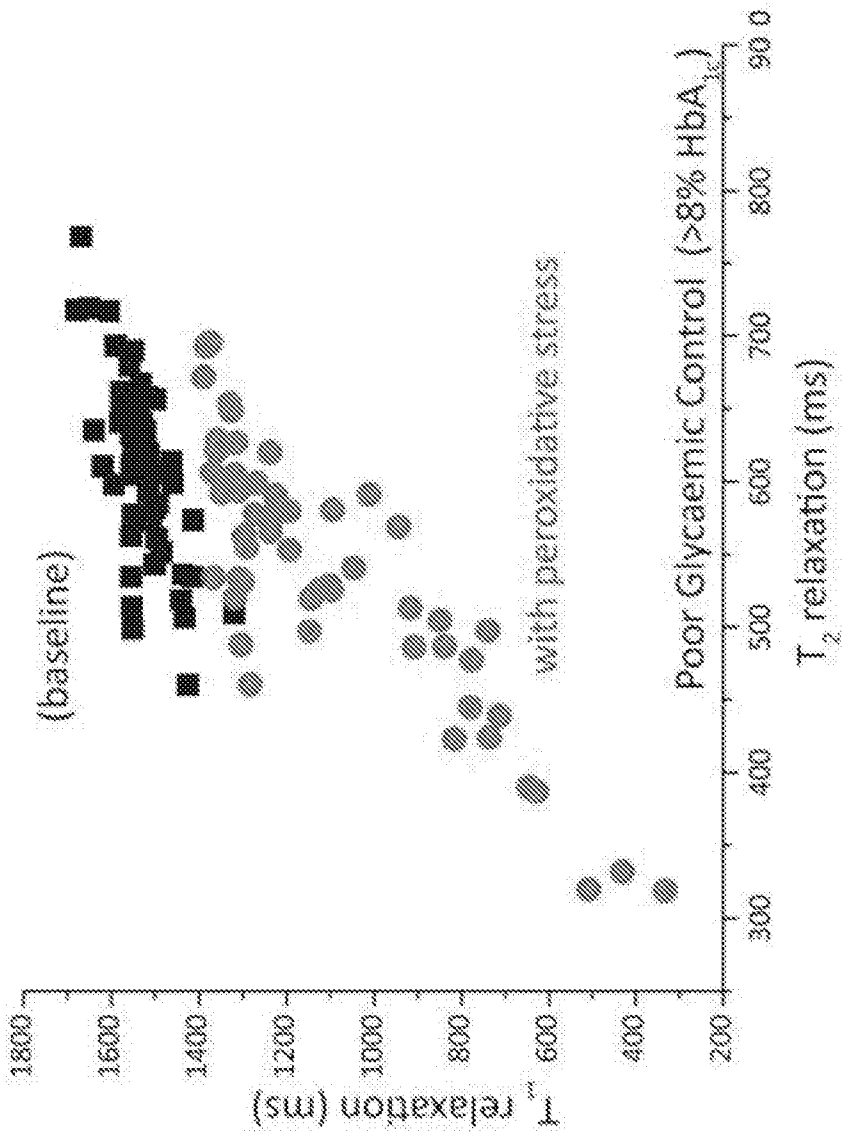


FIG. 6A

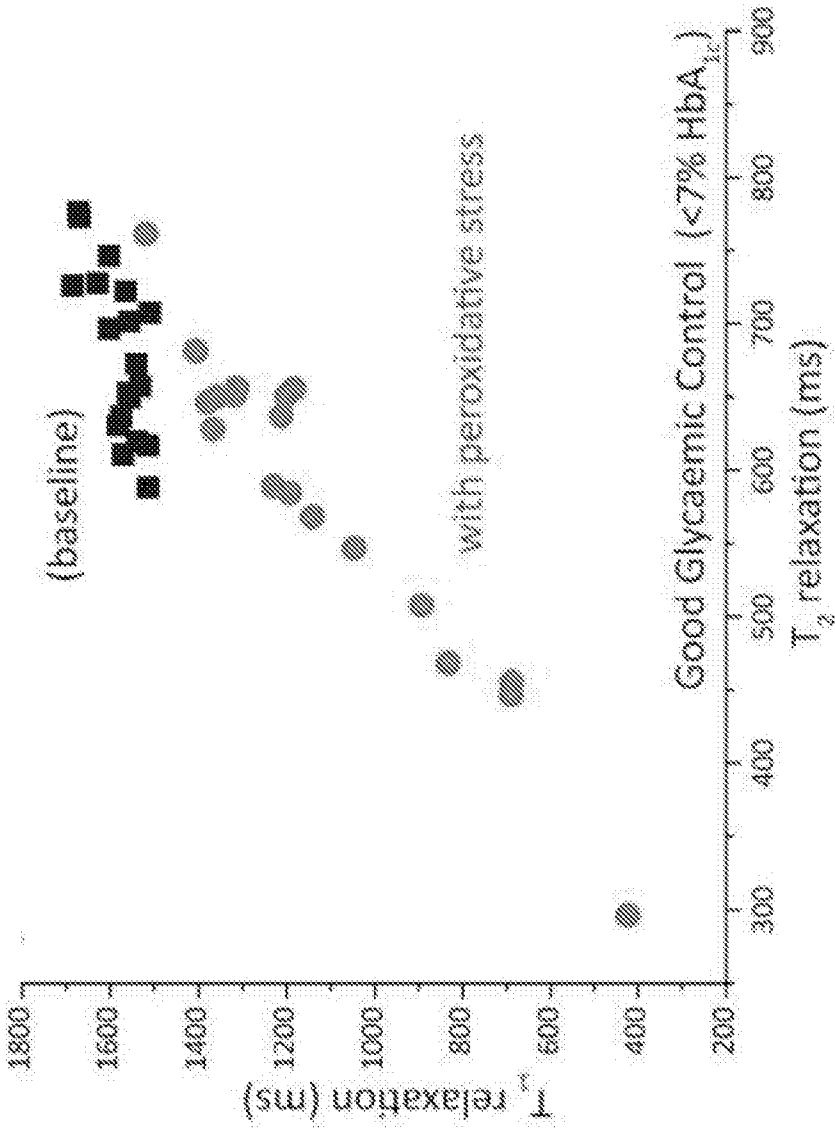


FIG. 6B

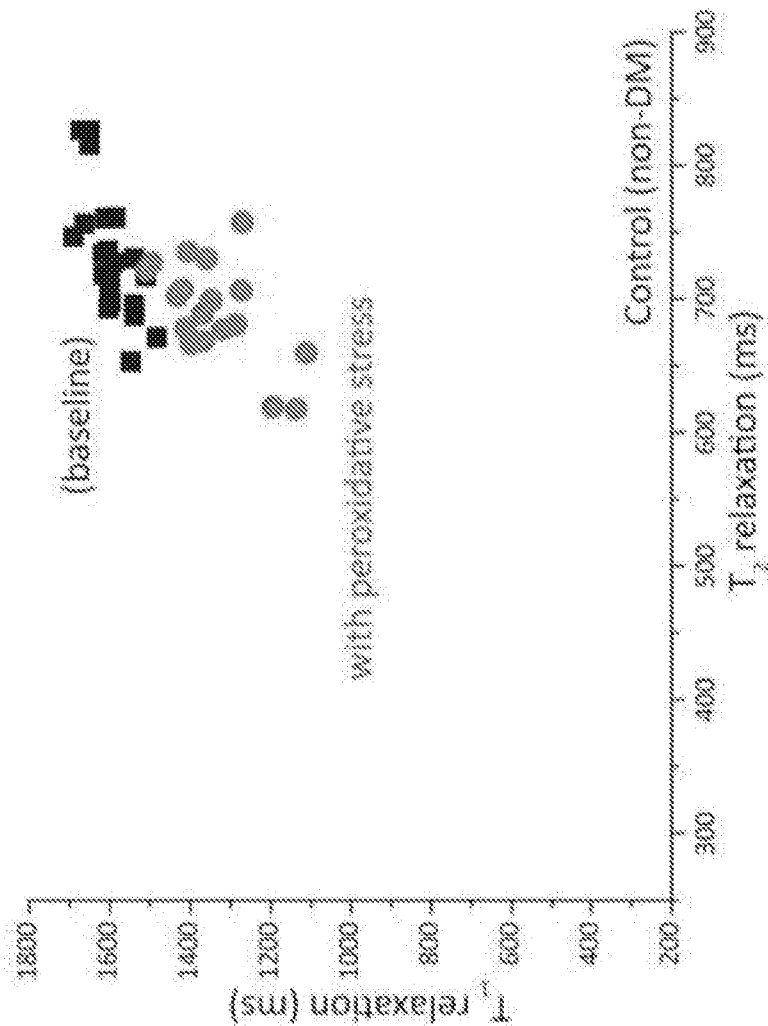


FIG. 6C

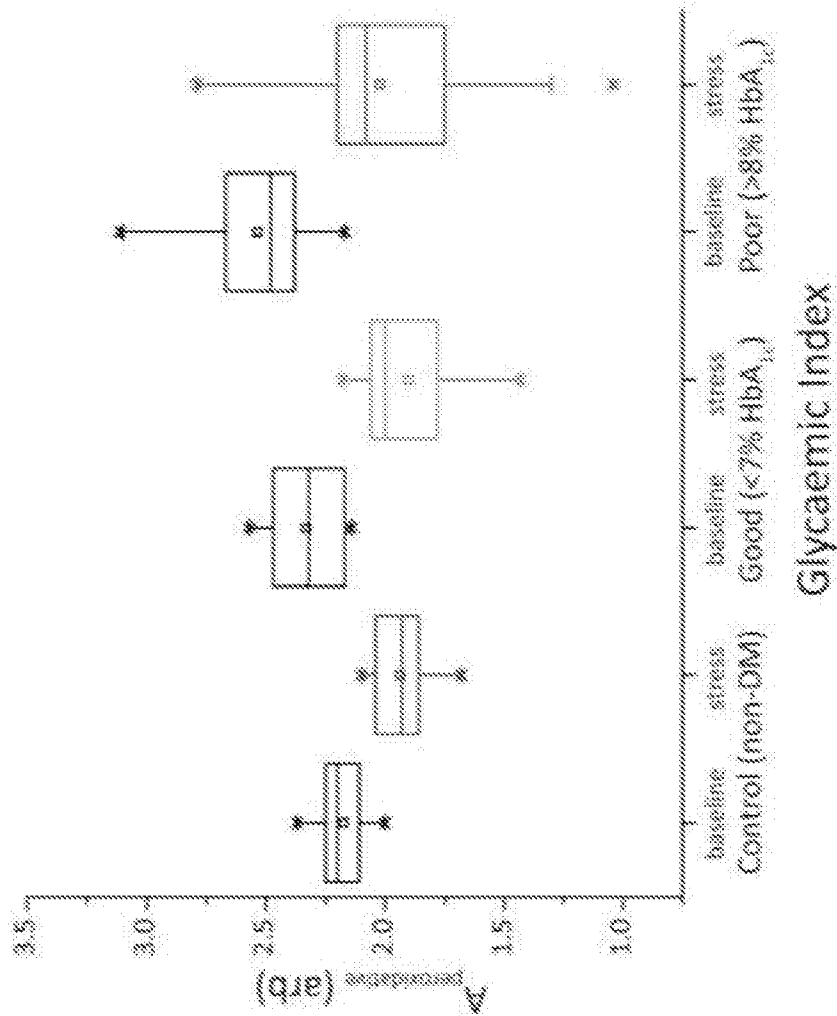


FIG. 6D

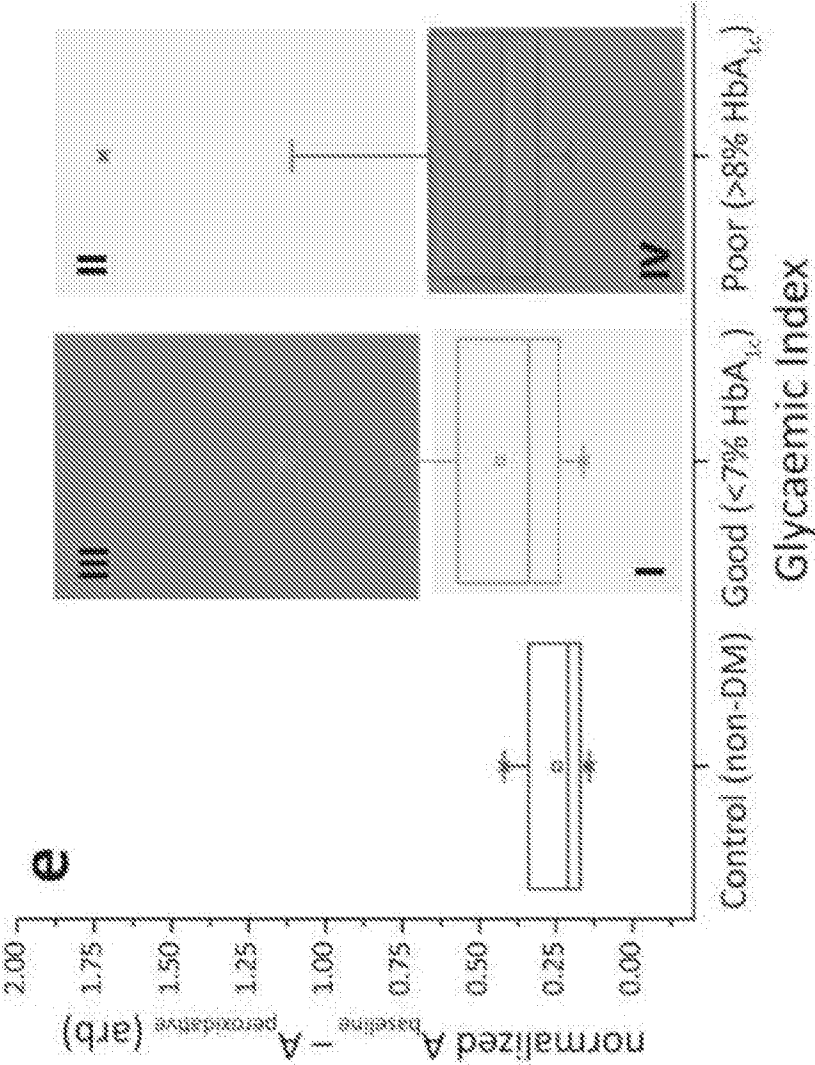


FIG. 6E

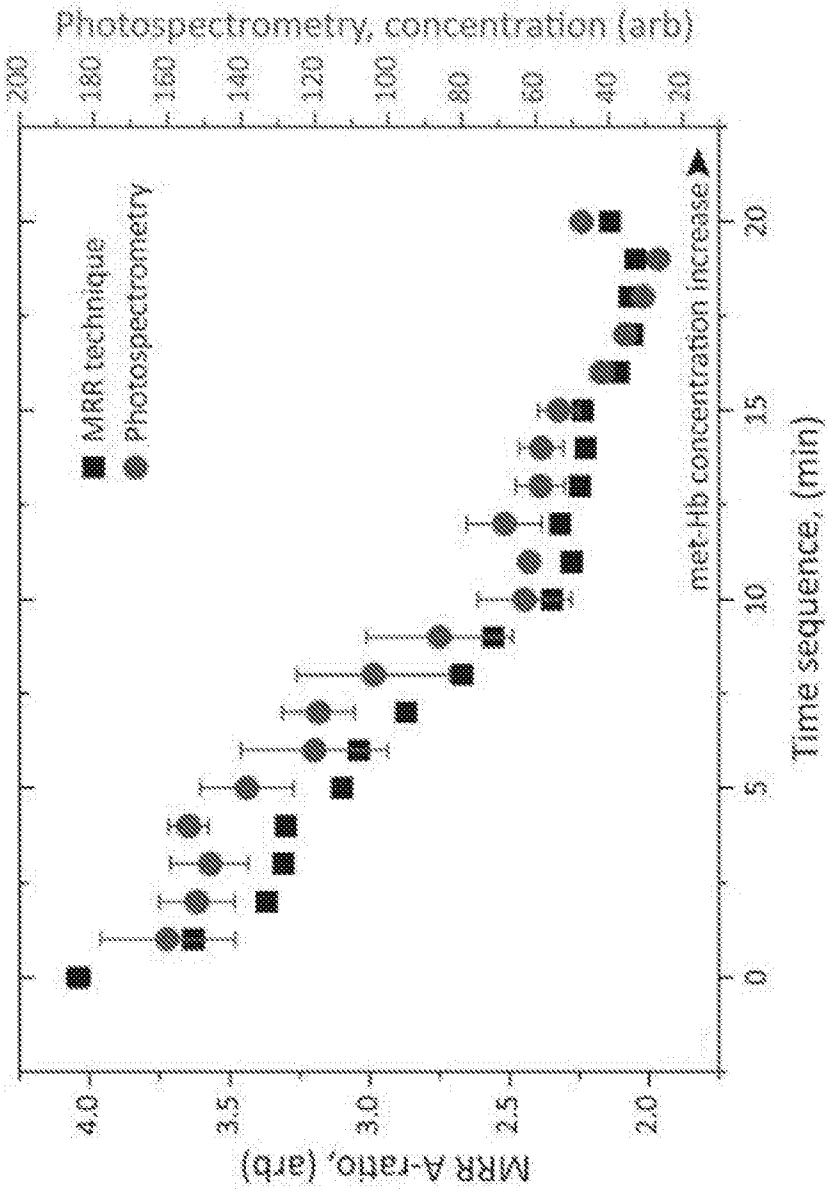
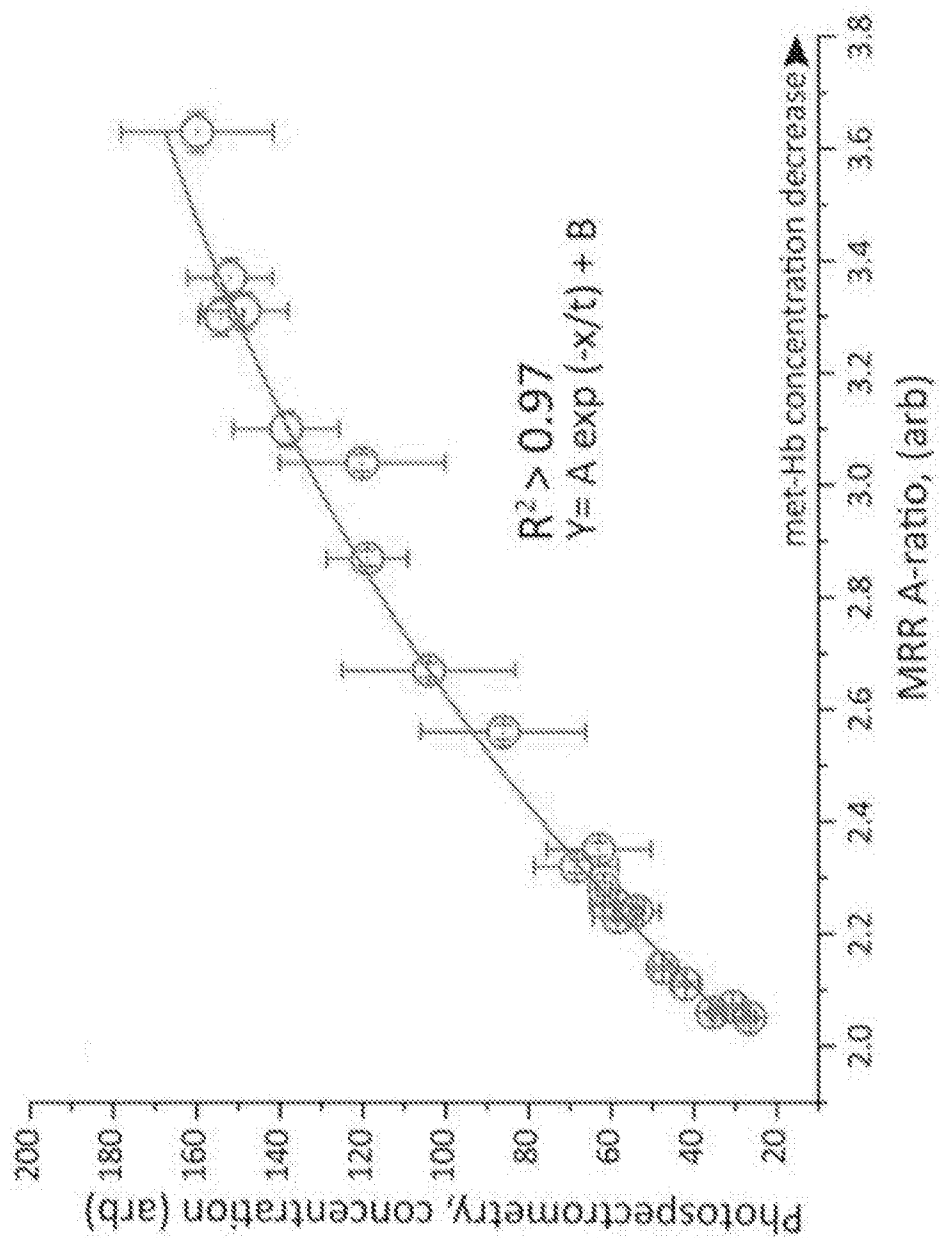


FIG. 7A

**FIG. 7B**

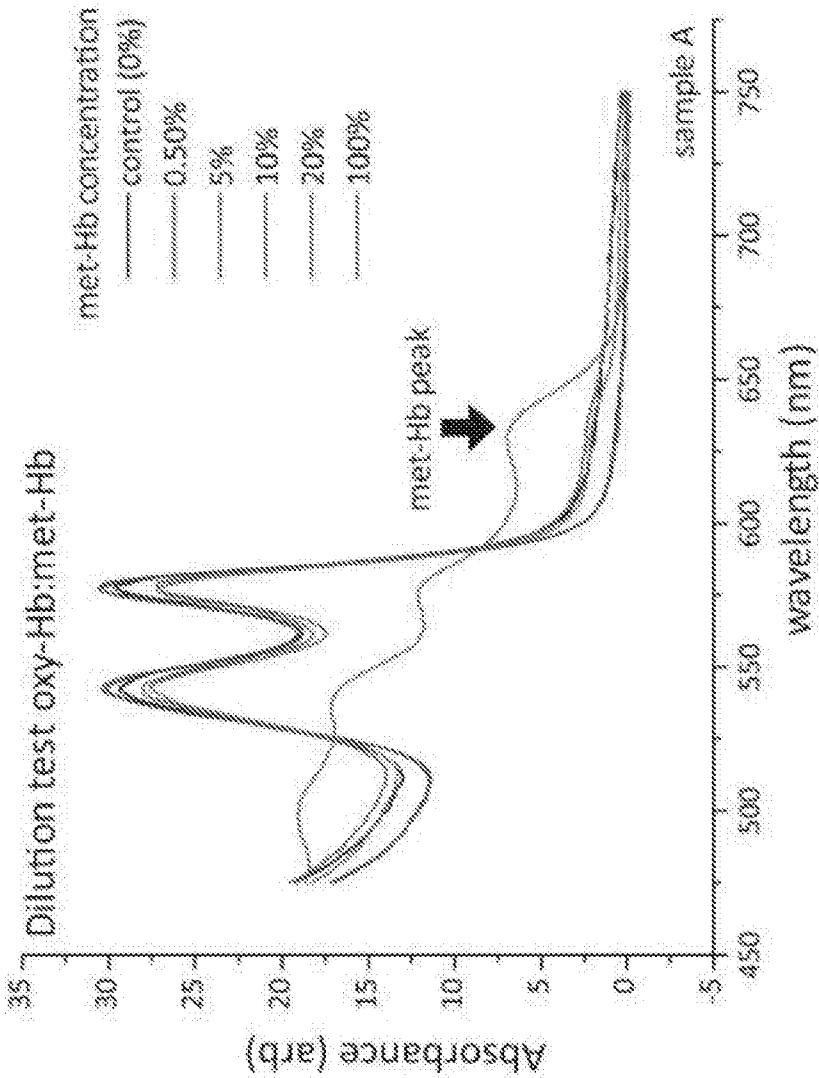


FIG. 8A

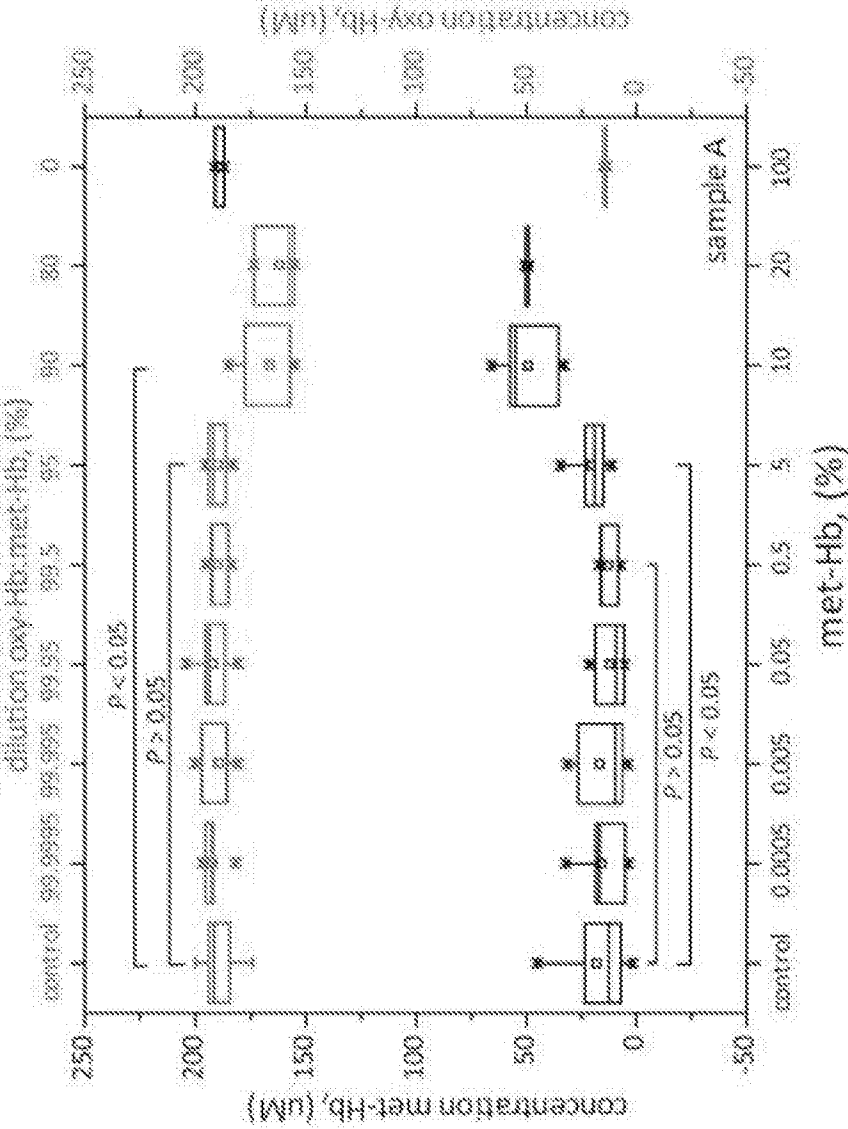


FIG. 8B

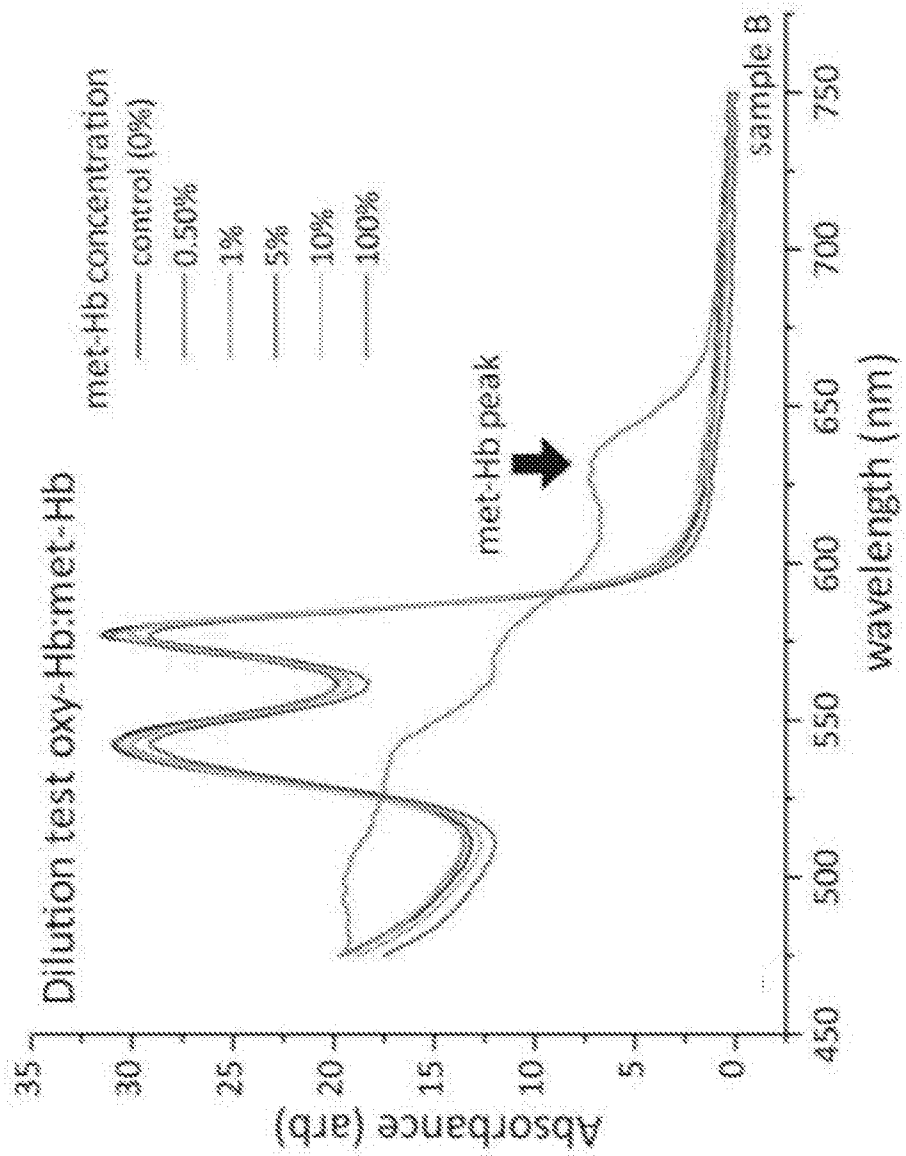


FIG. 8C

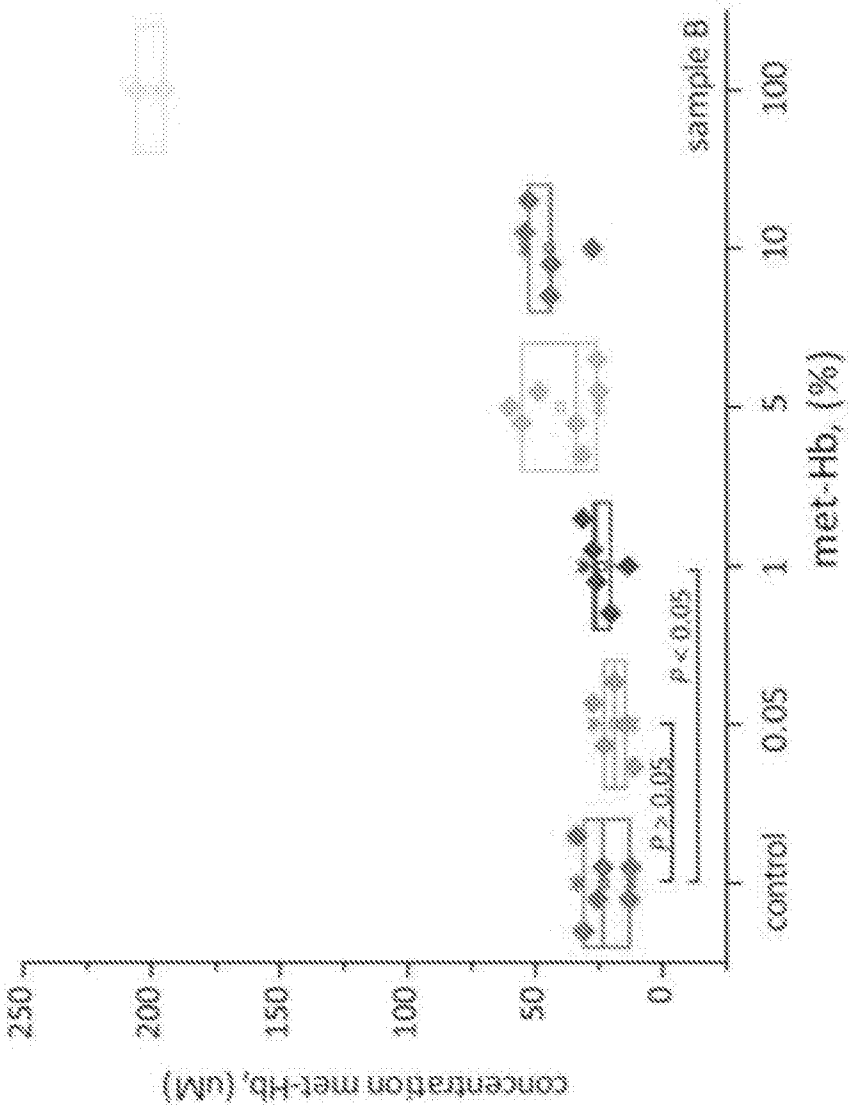


FIG. 8D

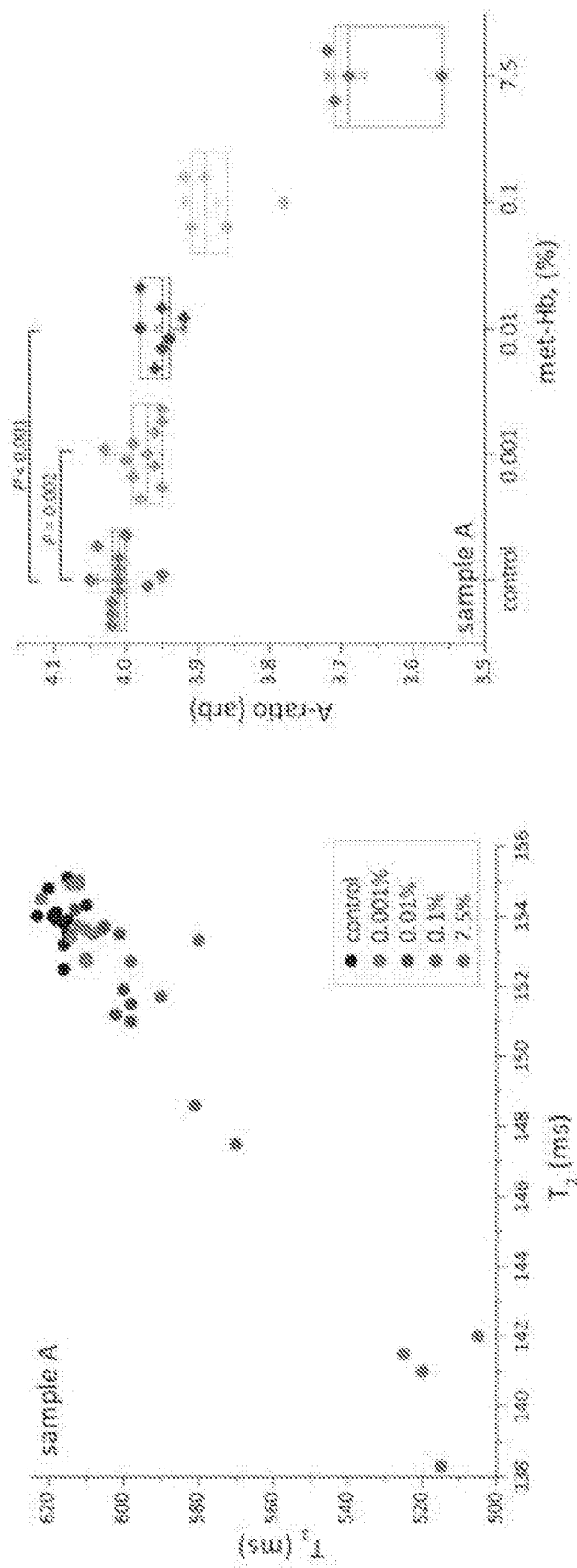


FIG. 9A

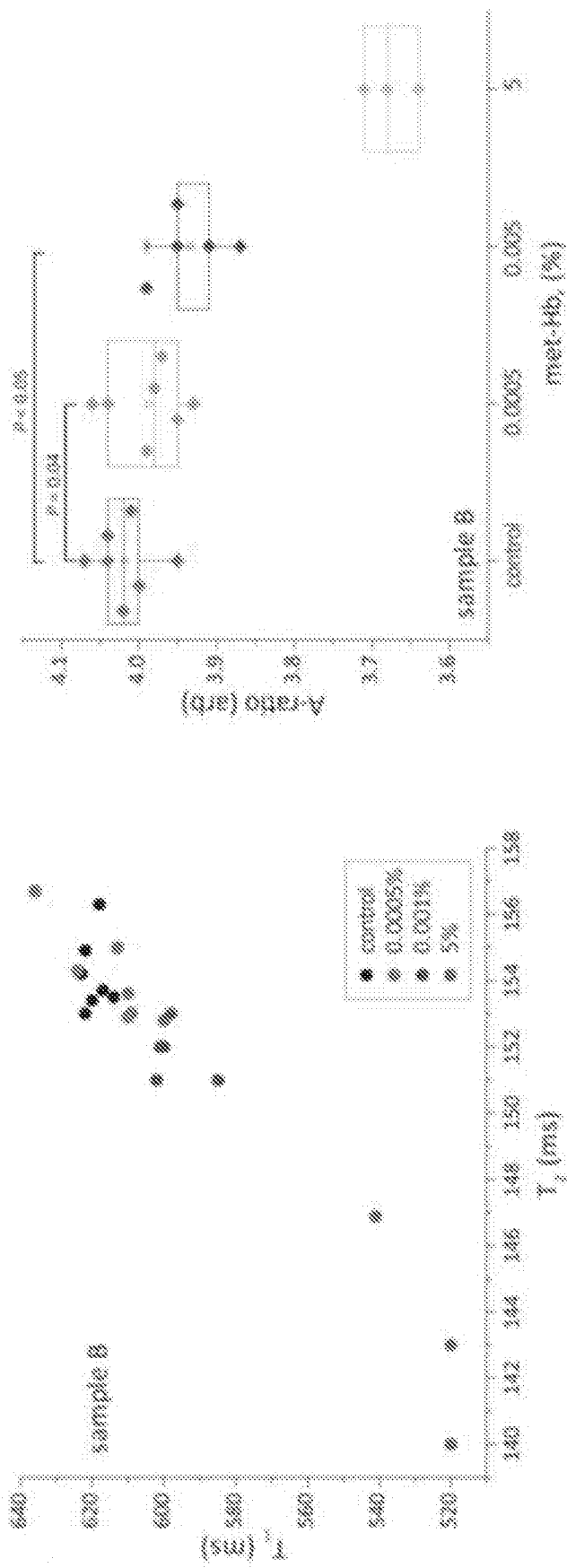


FIG. 9B

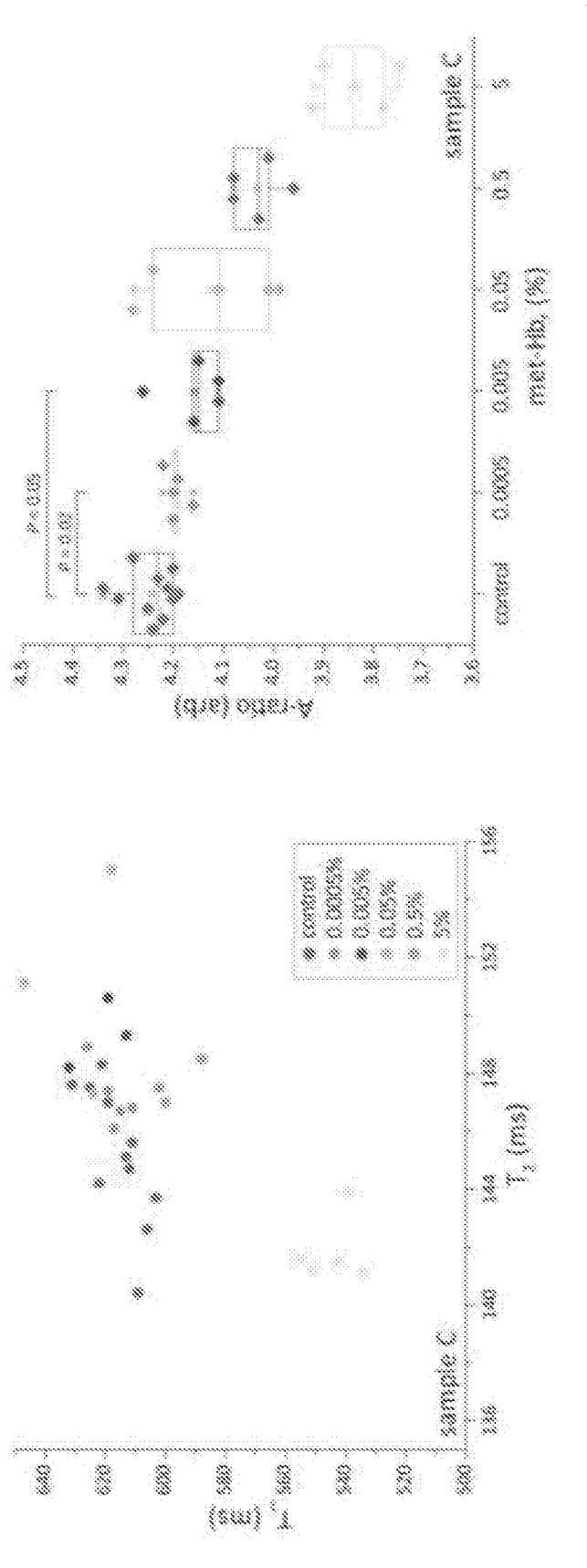


FIG. 9C

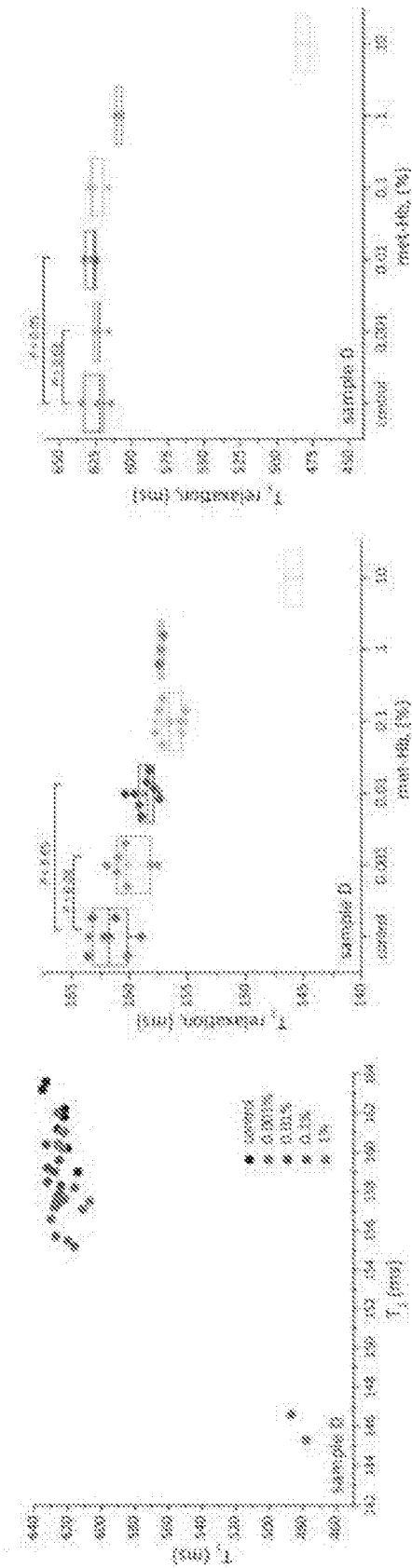


FIG. 9D

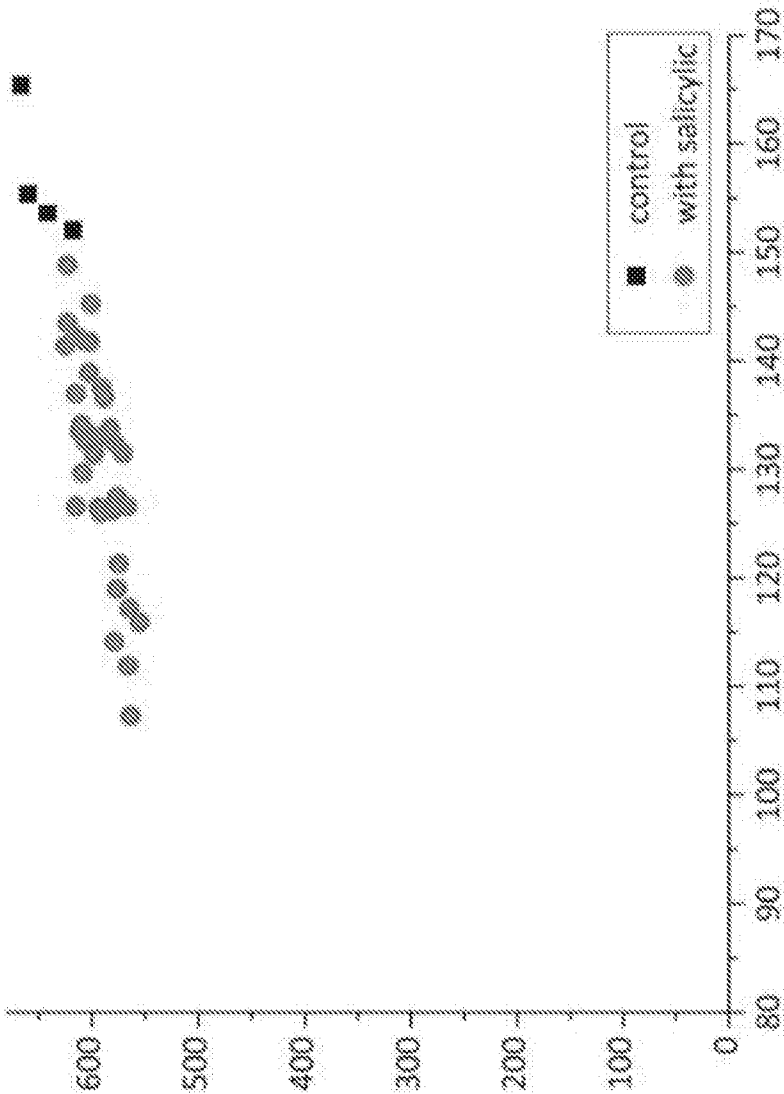


FIG. 10A

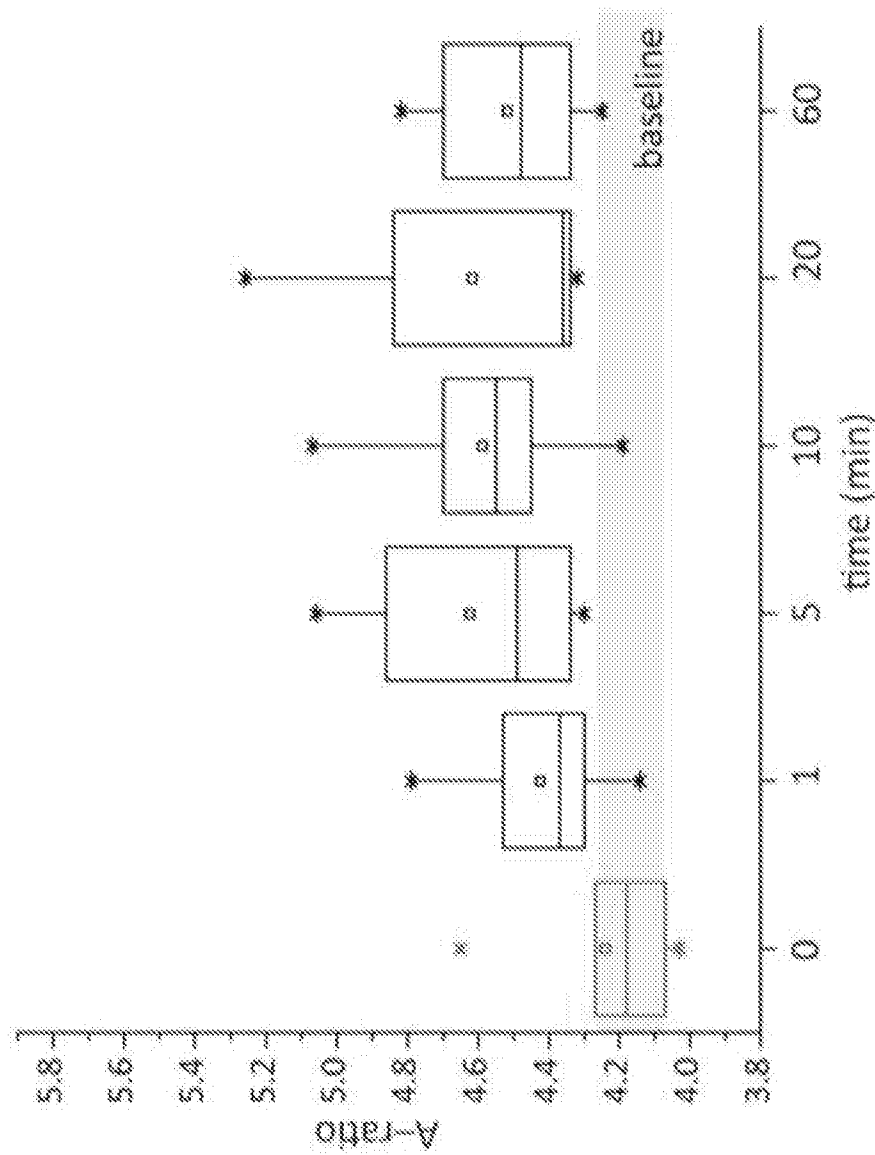


FIG. 10B

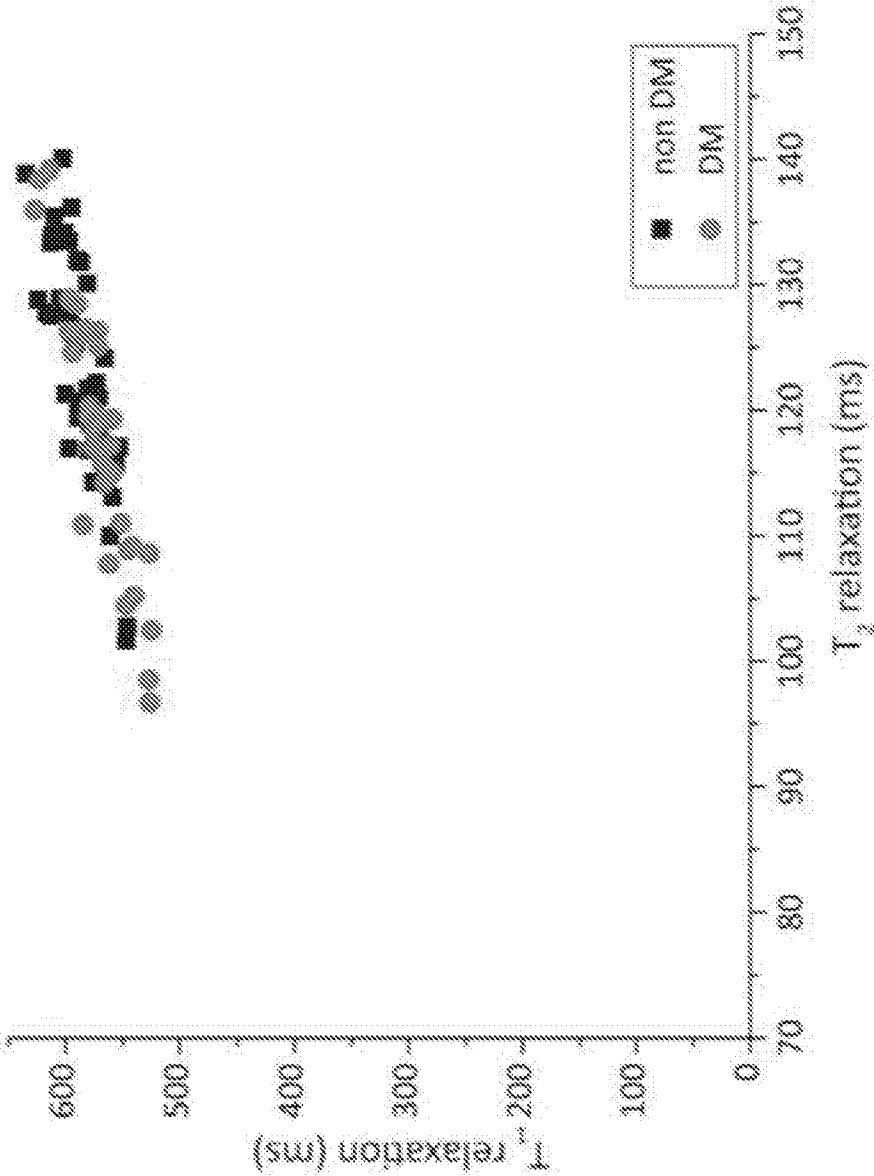


FIG. 10C

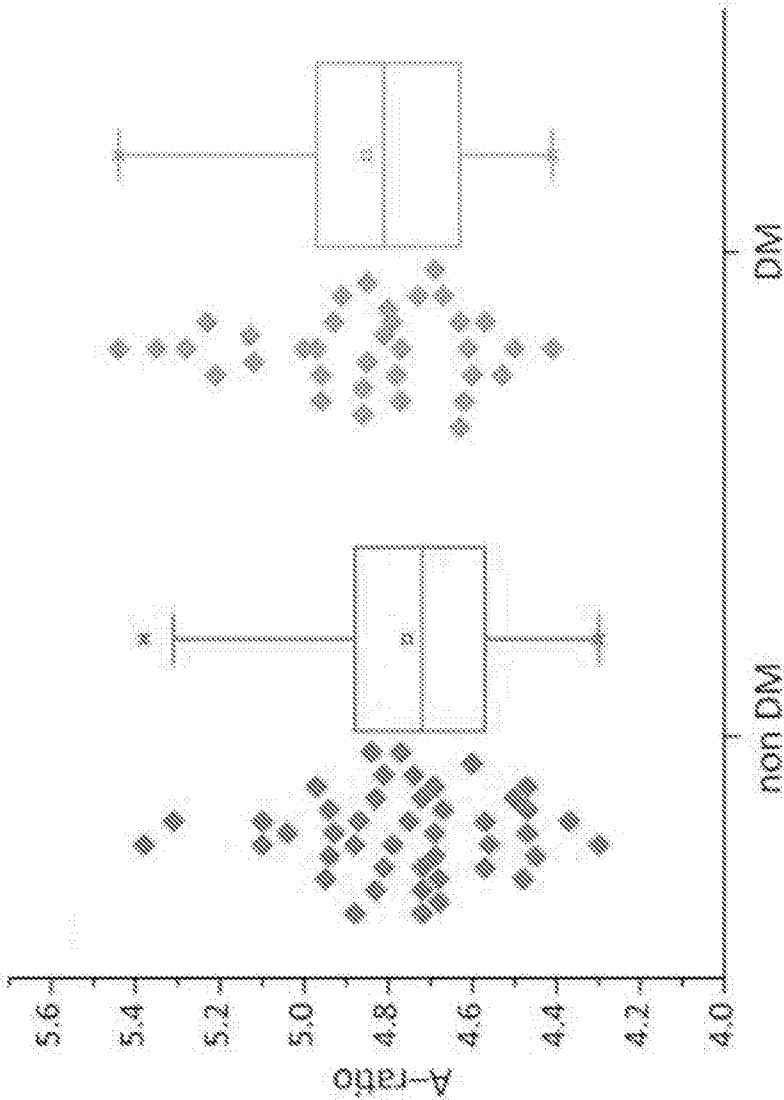


FIG. 10D

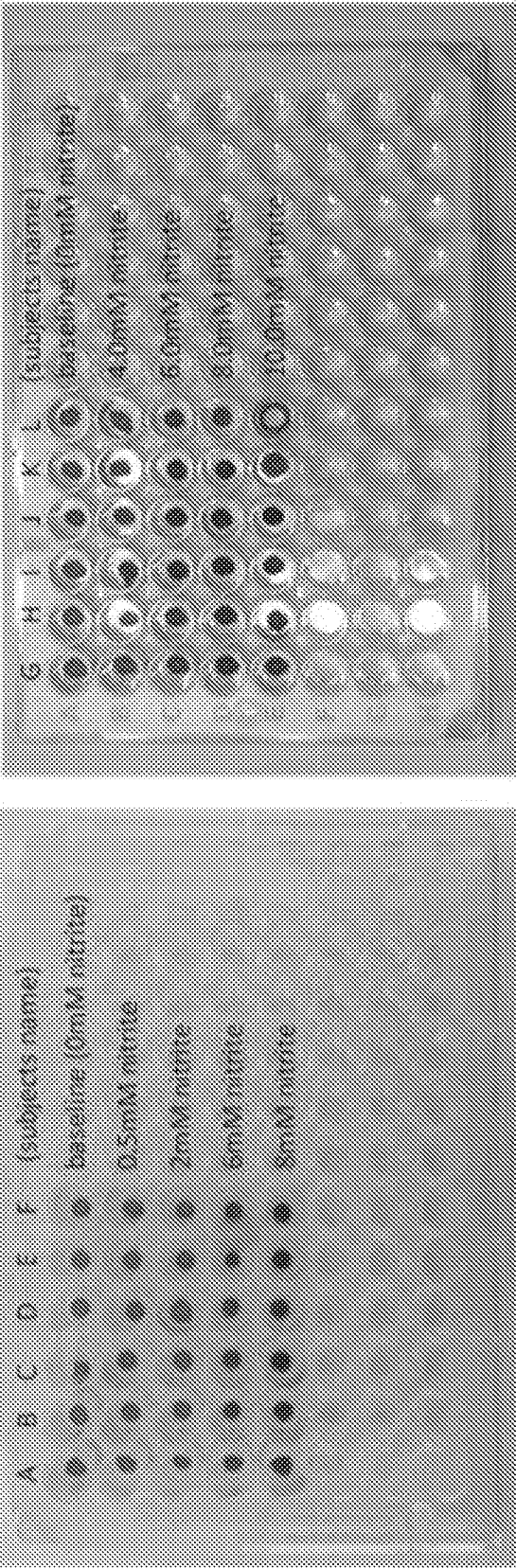


FIG. 11A

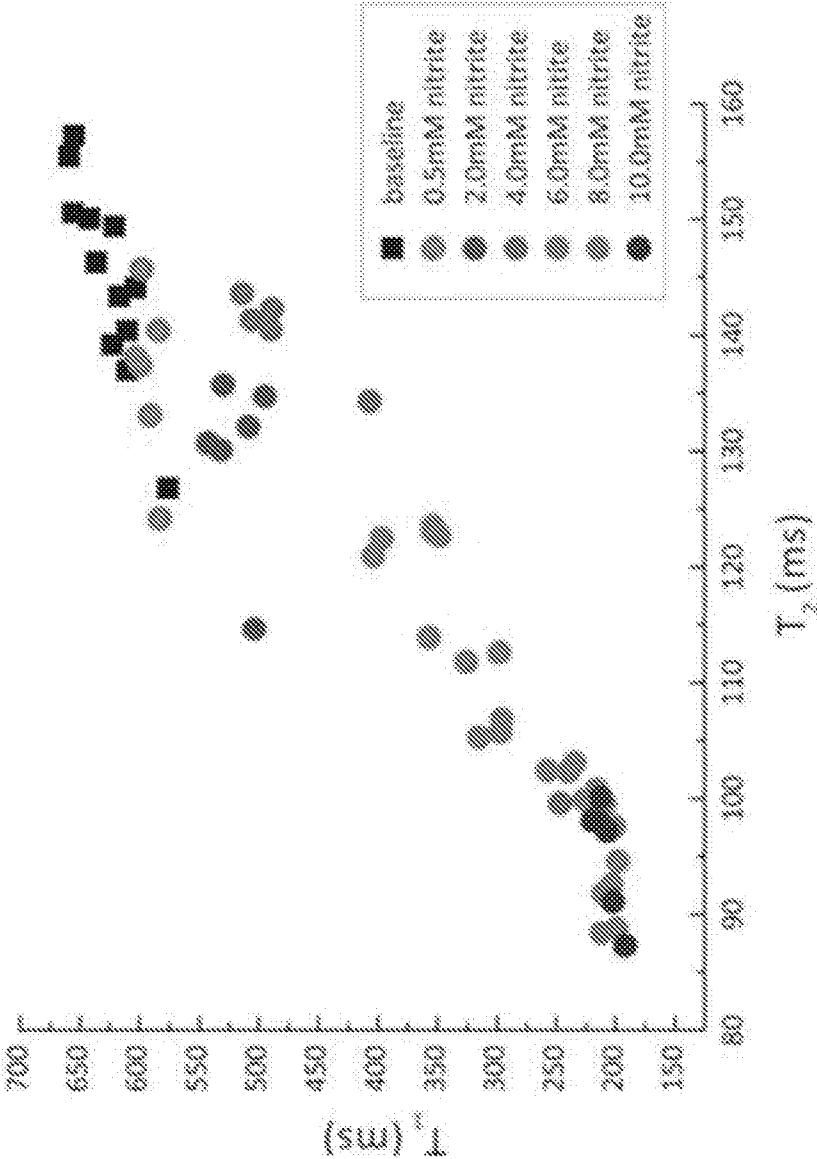


FIG. 11B

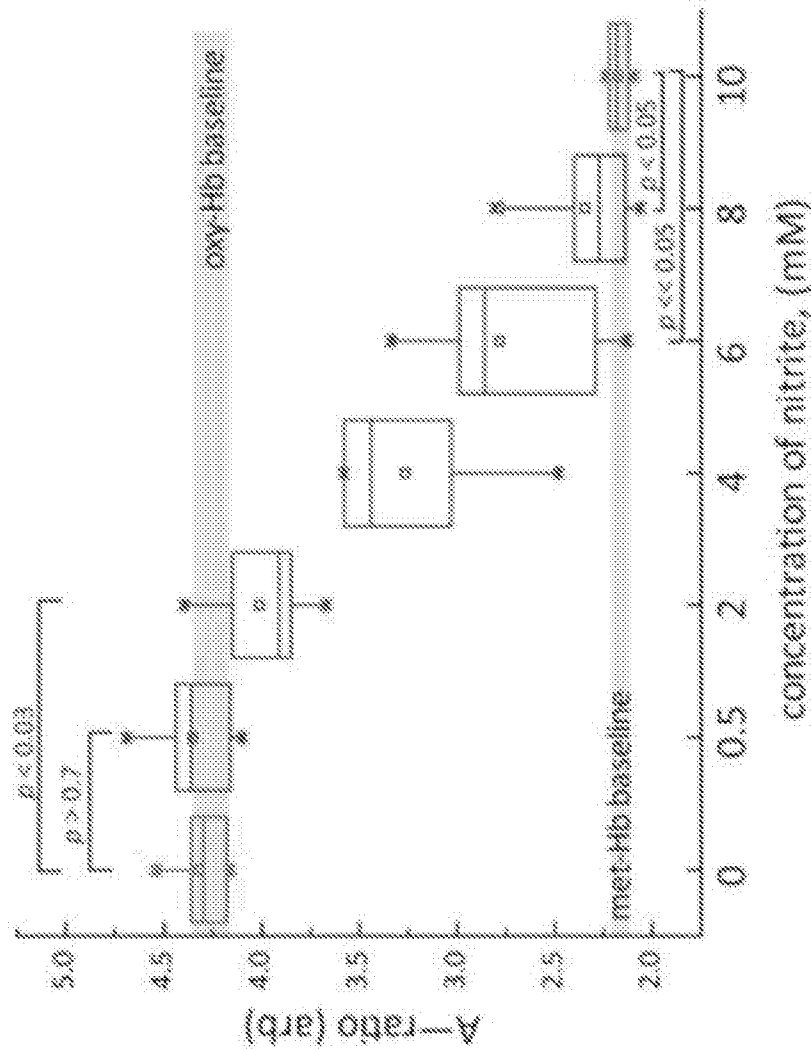


FIG. 11C

	ROC-AUC (nitrite concentration)						
	0mM	0.5mM	2.0mM	4.0mM	6.0mM	8.0mM	10mM
oxy-Hb baseline	-	0.444	0.875	1	1	1	1
met-Hb baseline	1	1	1	1	0.95	0.736	-

FIG. 11D

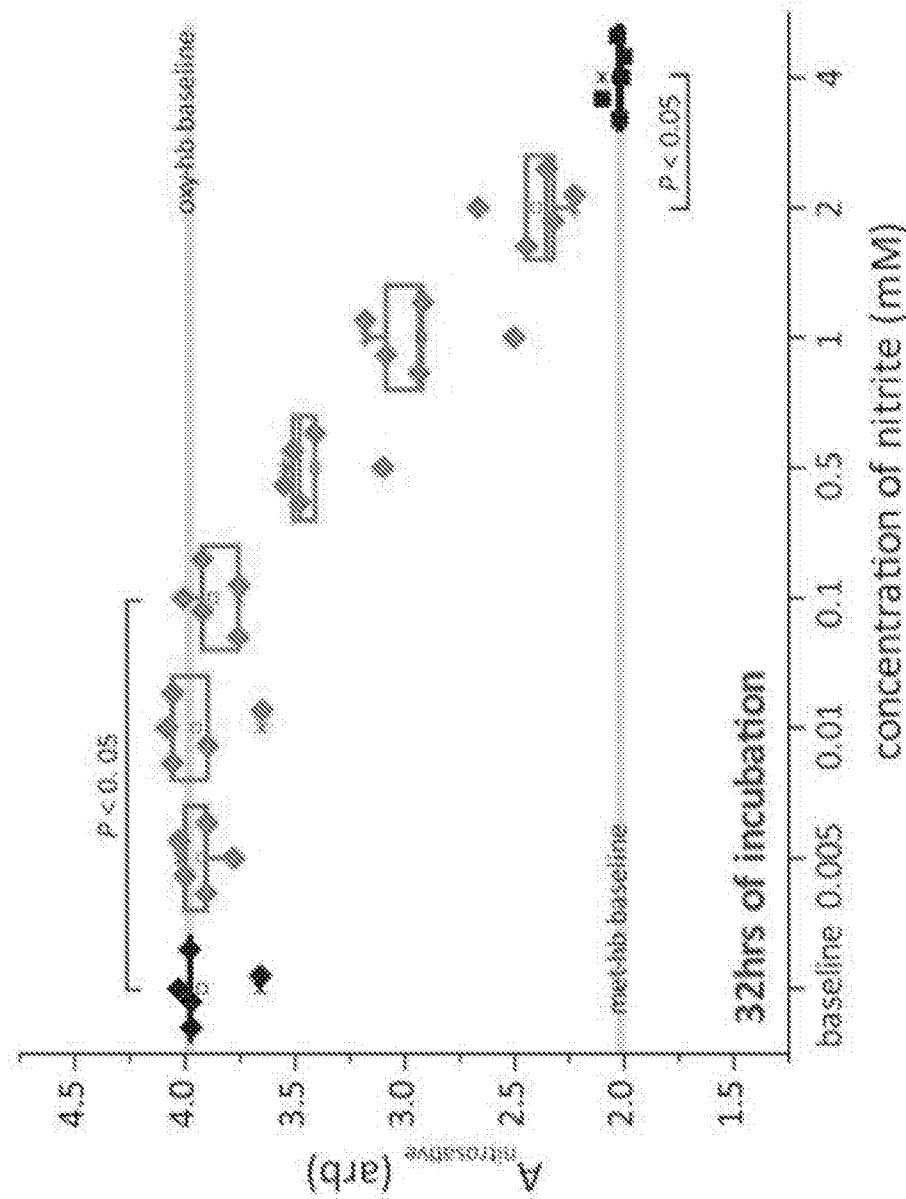


FIG. 12A

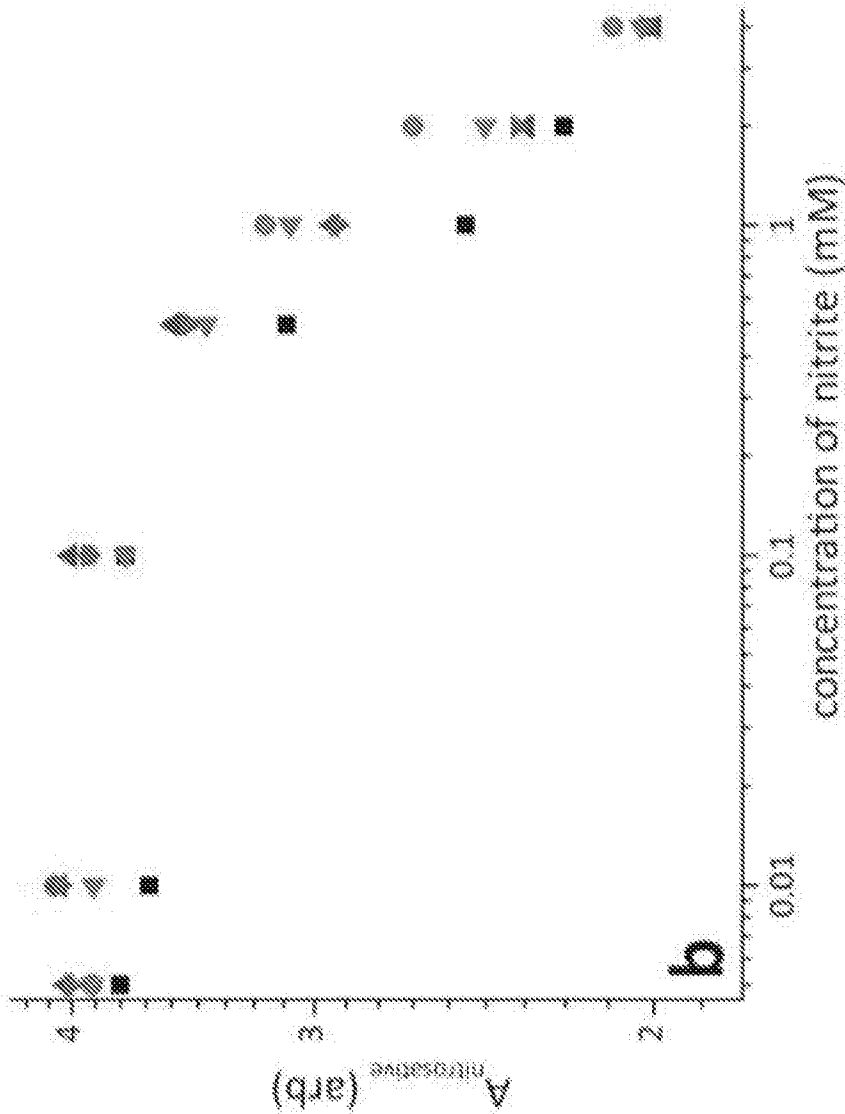


FIG. 12B

	ROC AUC: nitrite concentration (mM)							
	0	0.005	0.01	0.1	0.5	1	2	4
oxy-hb baseline	-	0.56	0.36	0.68	1	1	1	1
met-hb baseline	1	1	1	1	1	1	1	-

FIG. 12C

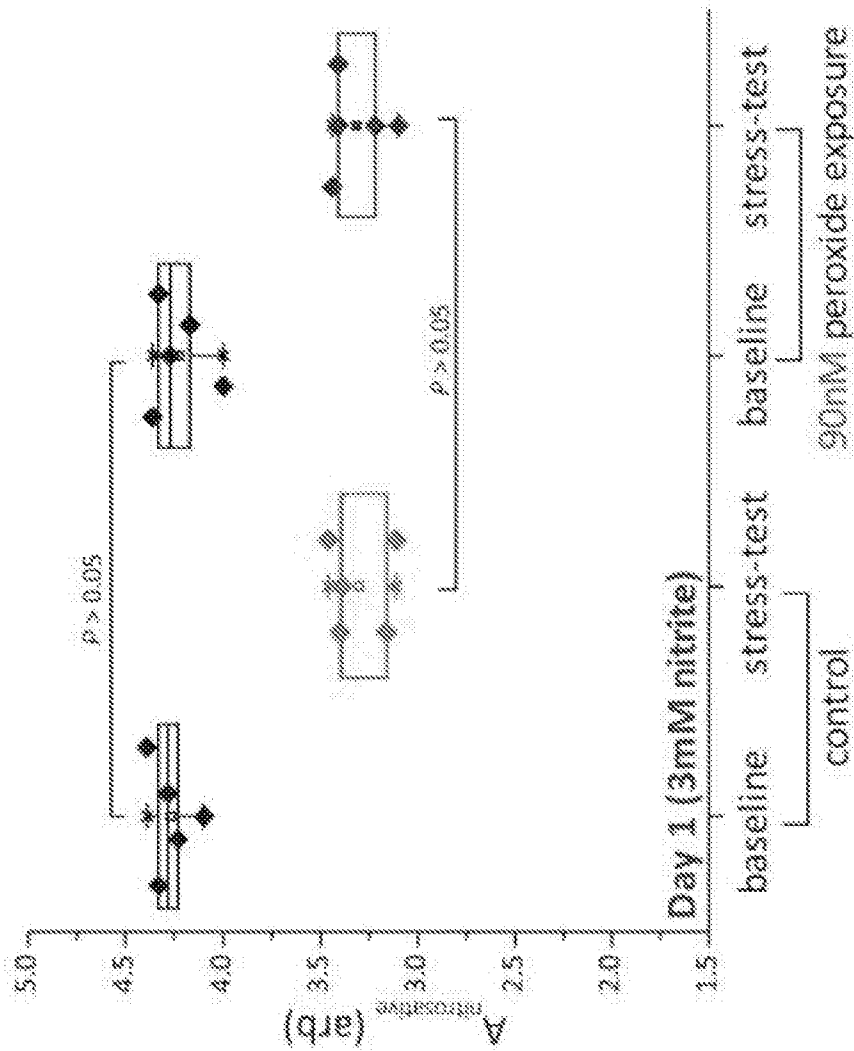


FIG. 13A

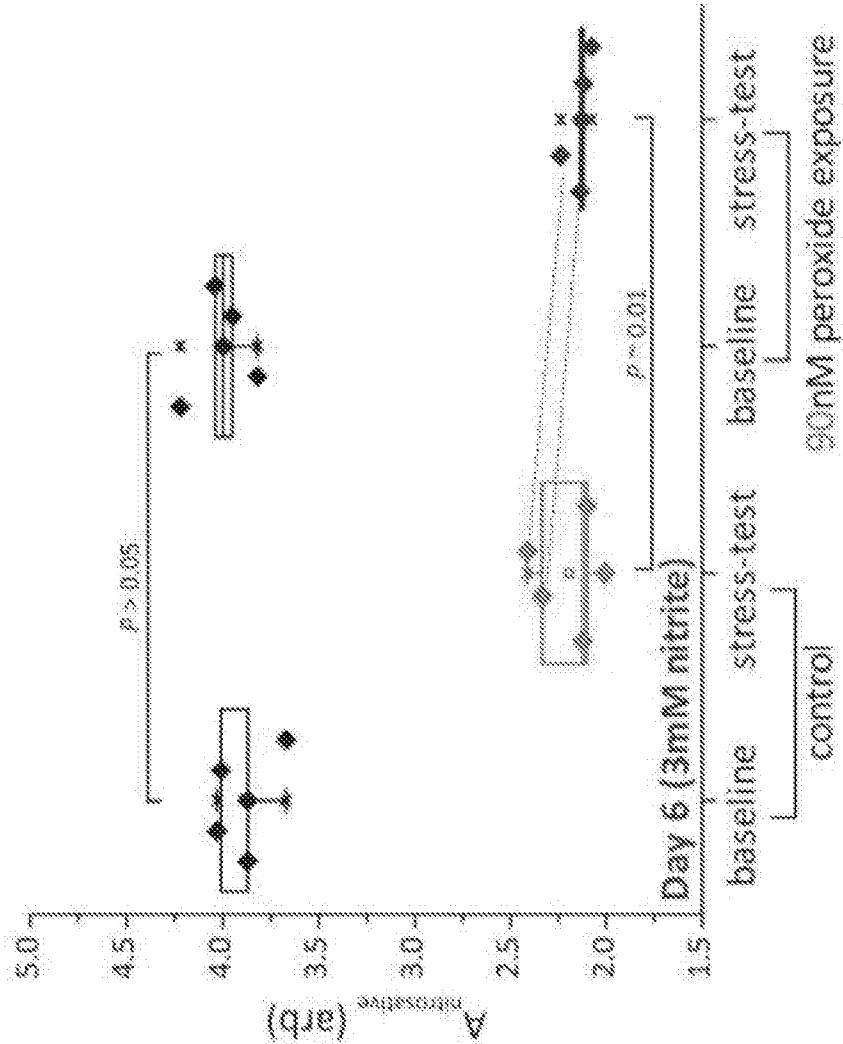


FIG. 13B

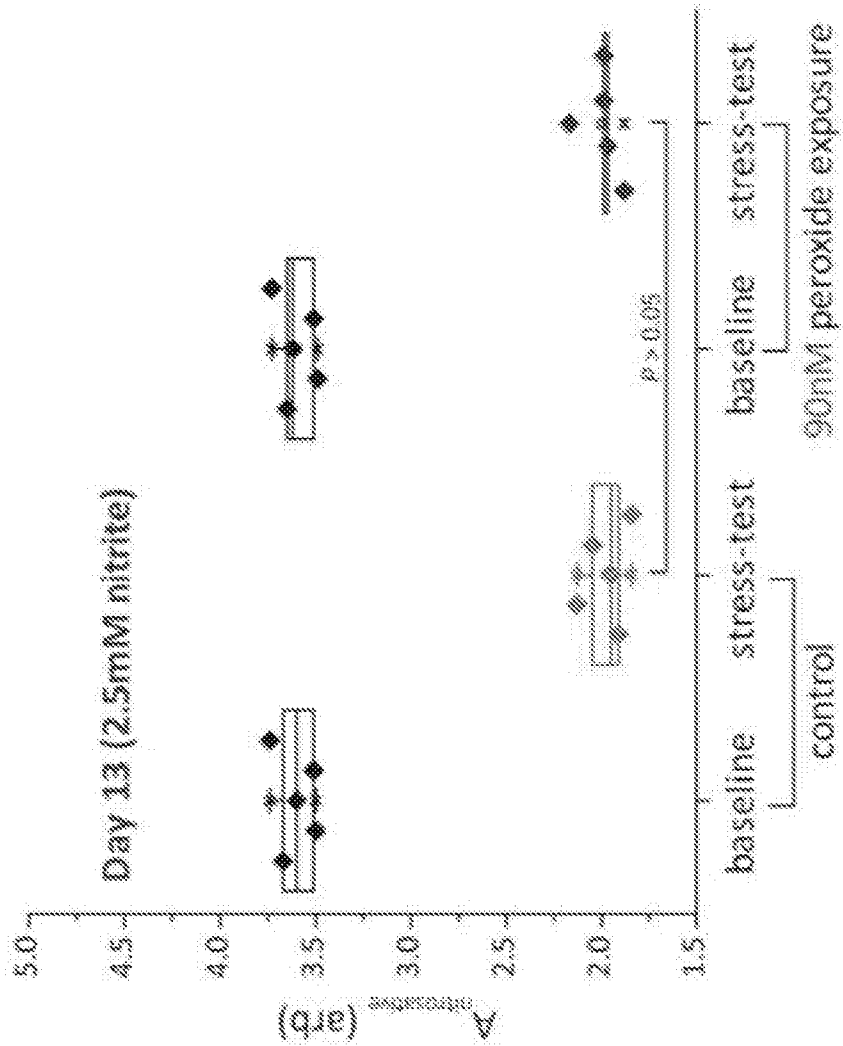


FIG. 13C

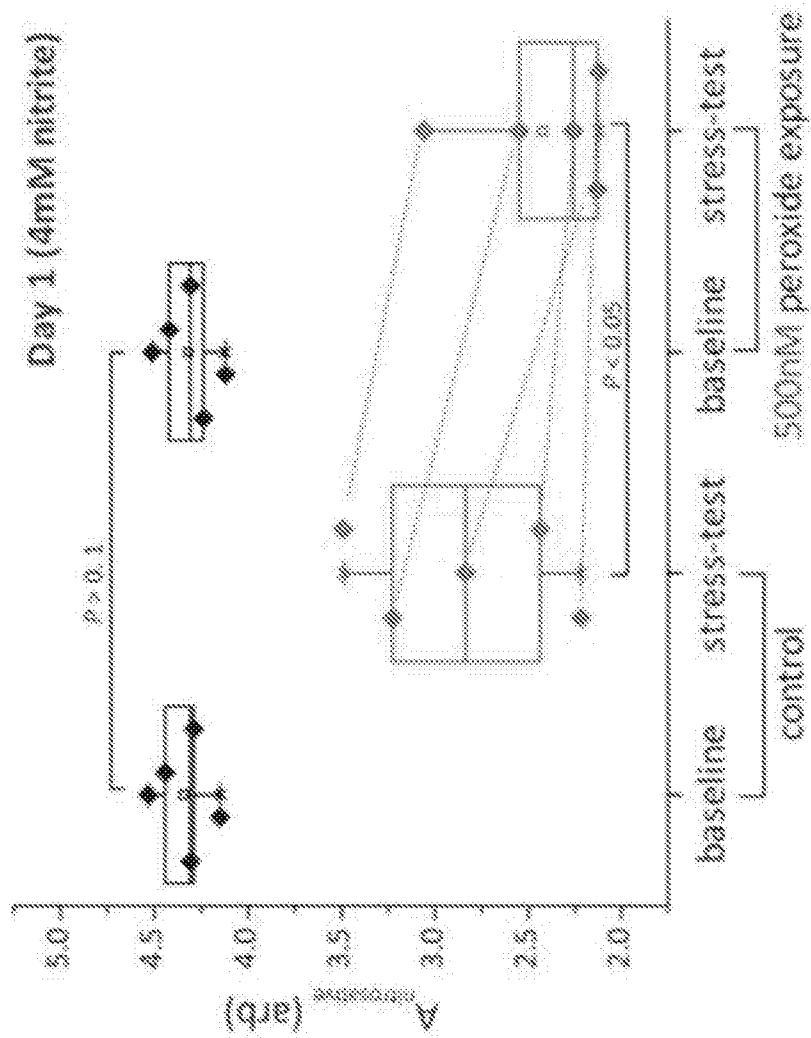


FIG. 13D

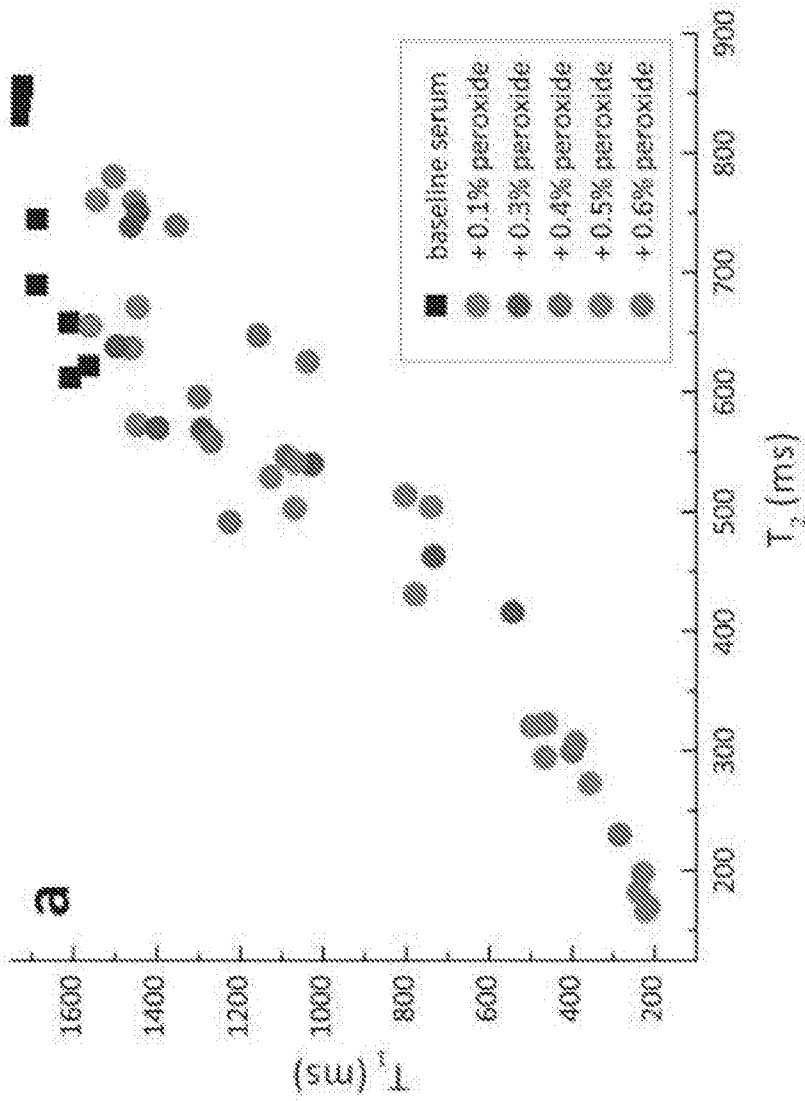


FIG. 14A

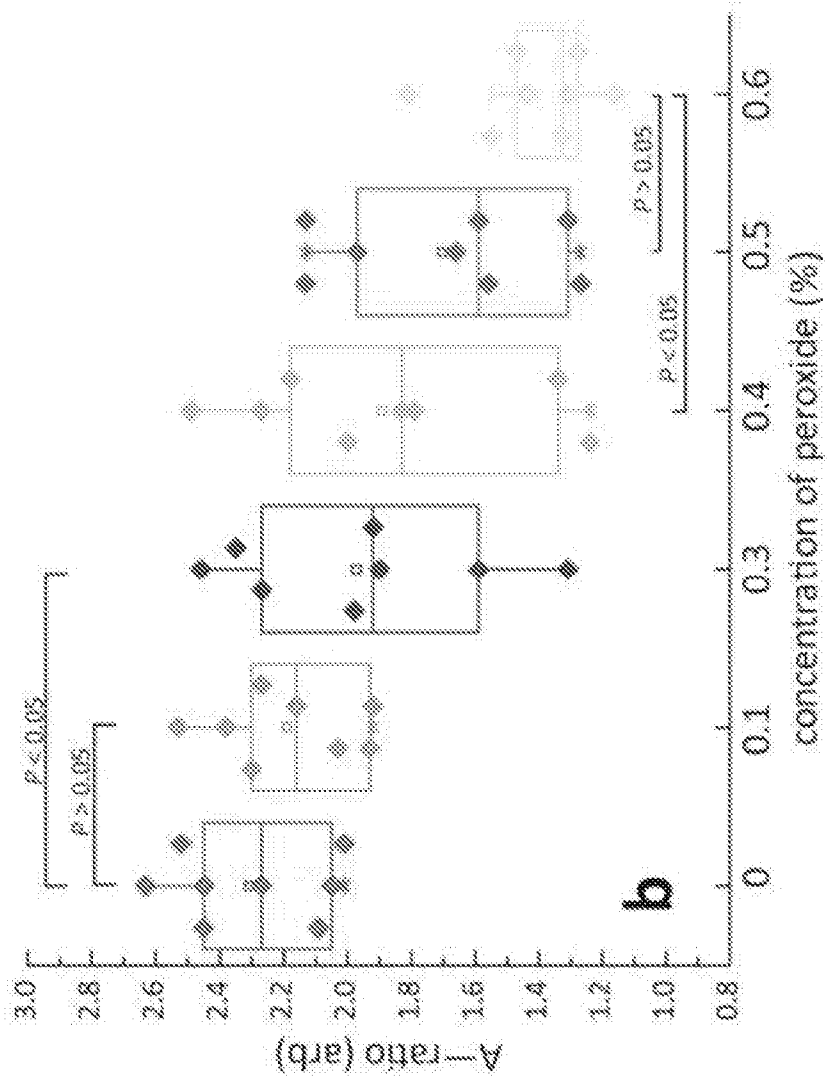


FIG. 14B

	ROC-AUC (Peroxide concentration)					
	0	0.10%	0.30%	0.40%	0.50%	0.60%
baseline	-	0.64	0.8	0.81	0.9	1
baseline (oxidized)	1	1	0.9	0.82	0.76	-

FIG. 14C

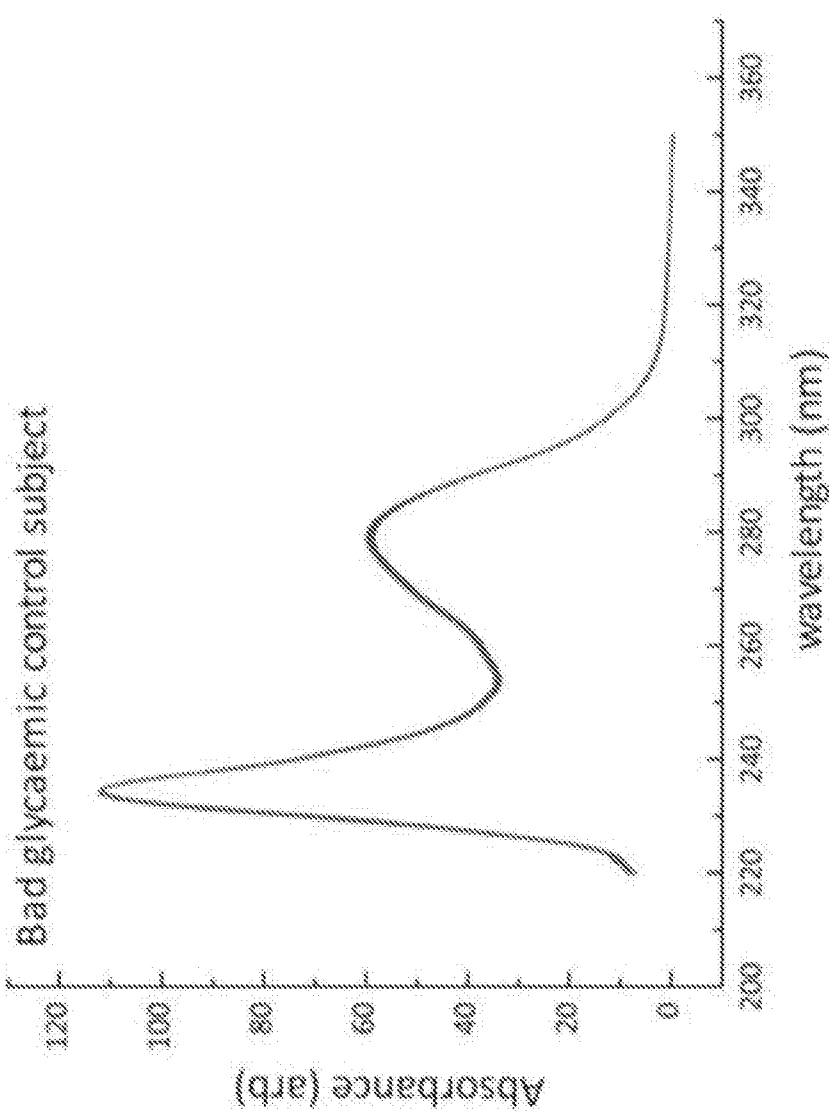


FIG. 14D

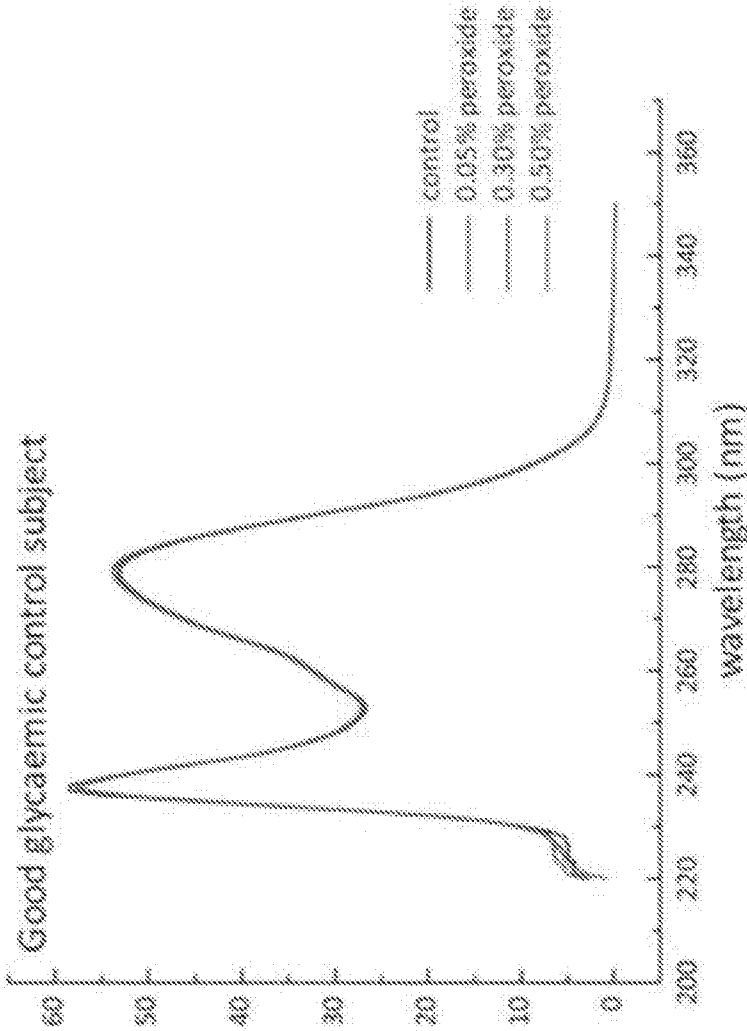


FIG. 14E

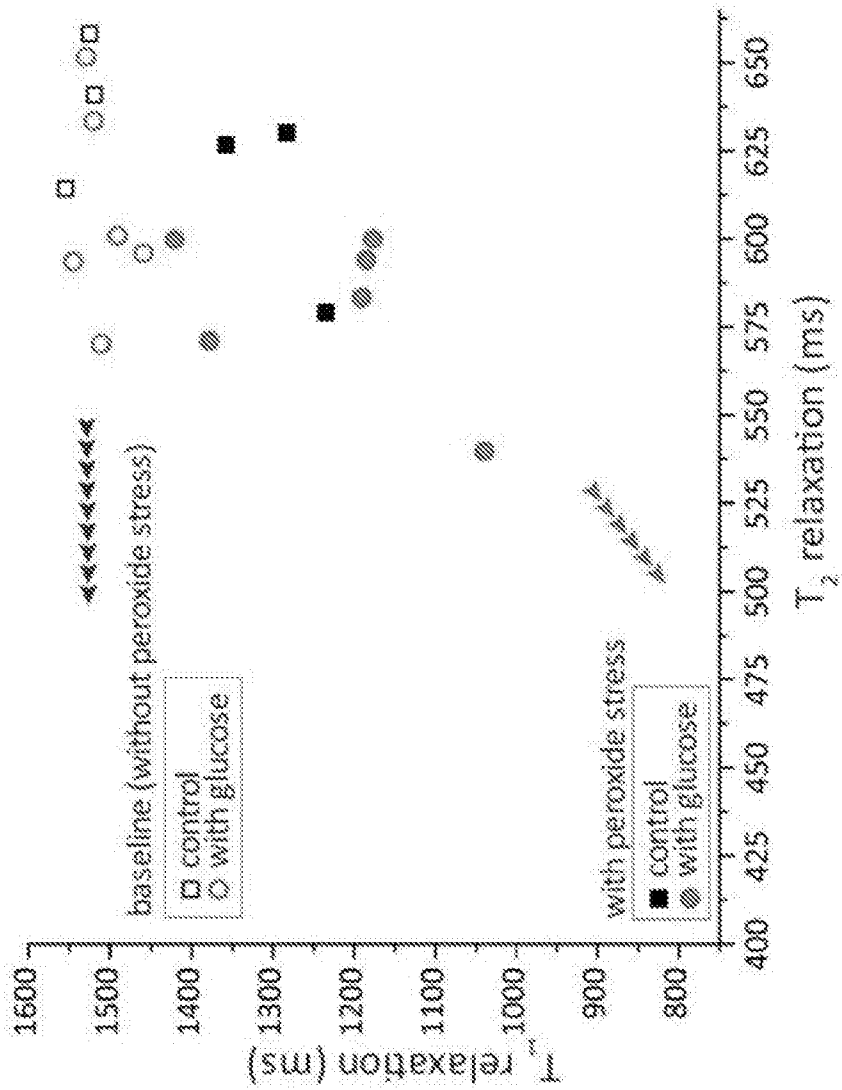


FIG. 15A

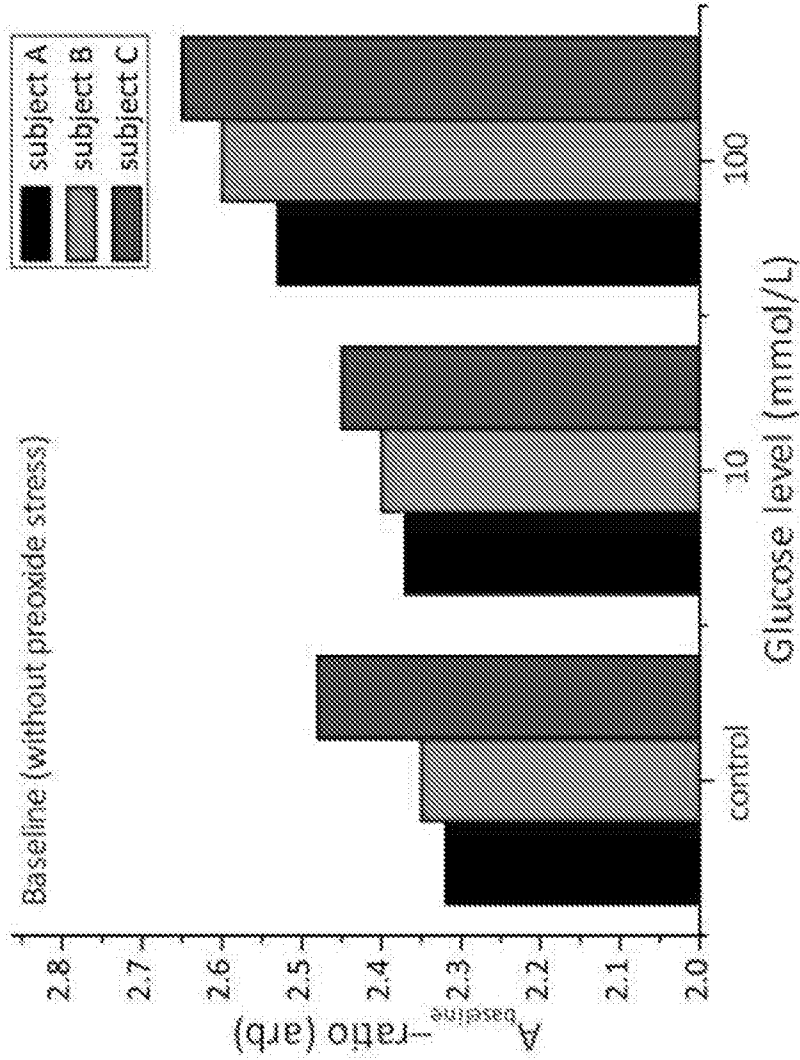


FIG. 15B

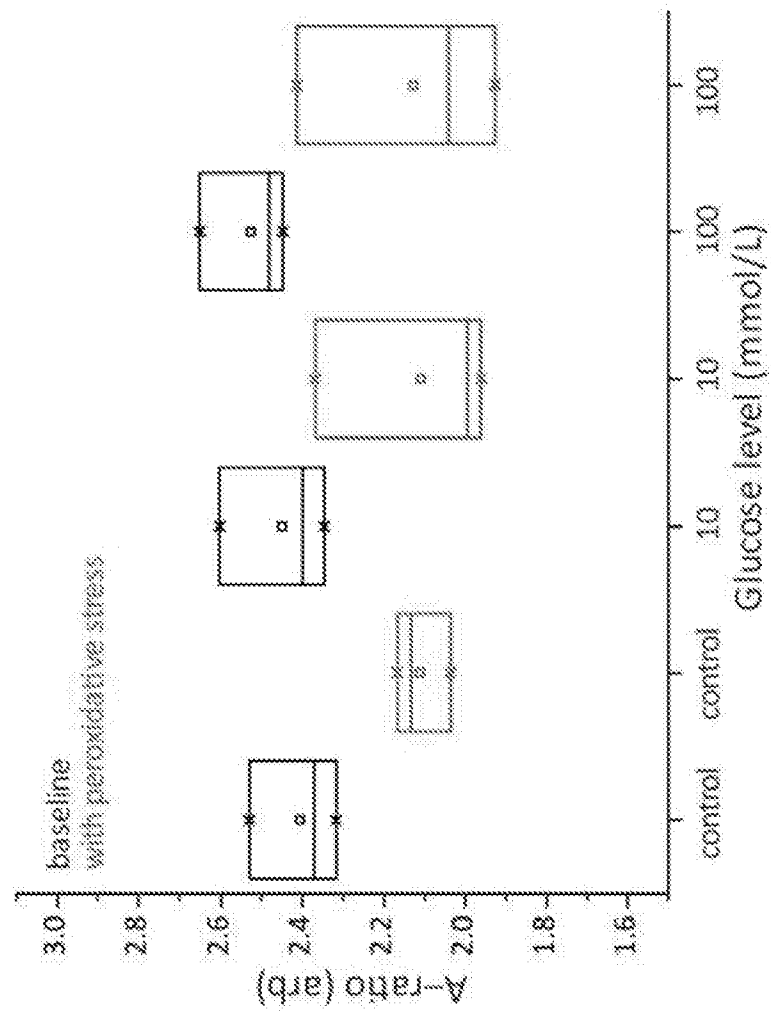


FIG. 15C

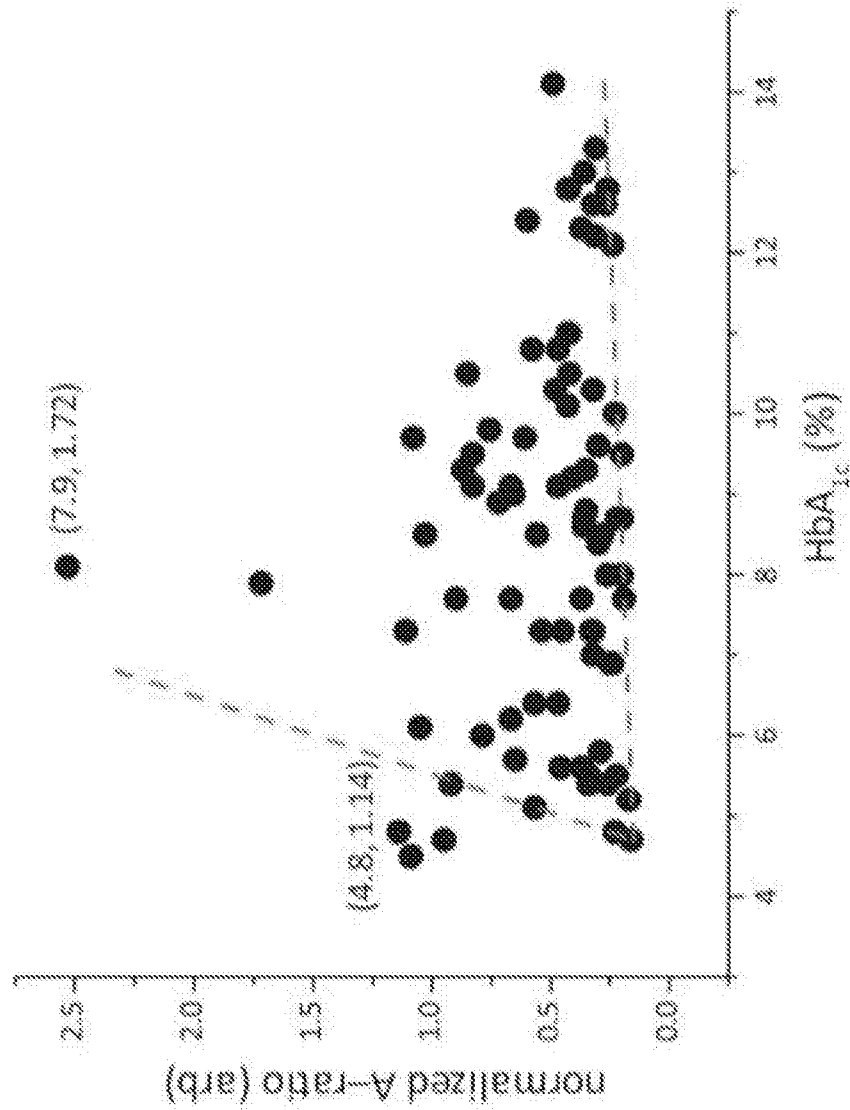


FIG. 16A

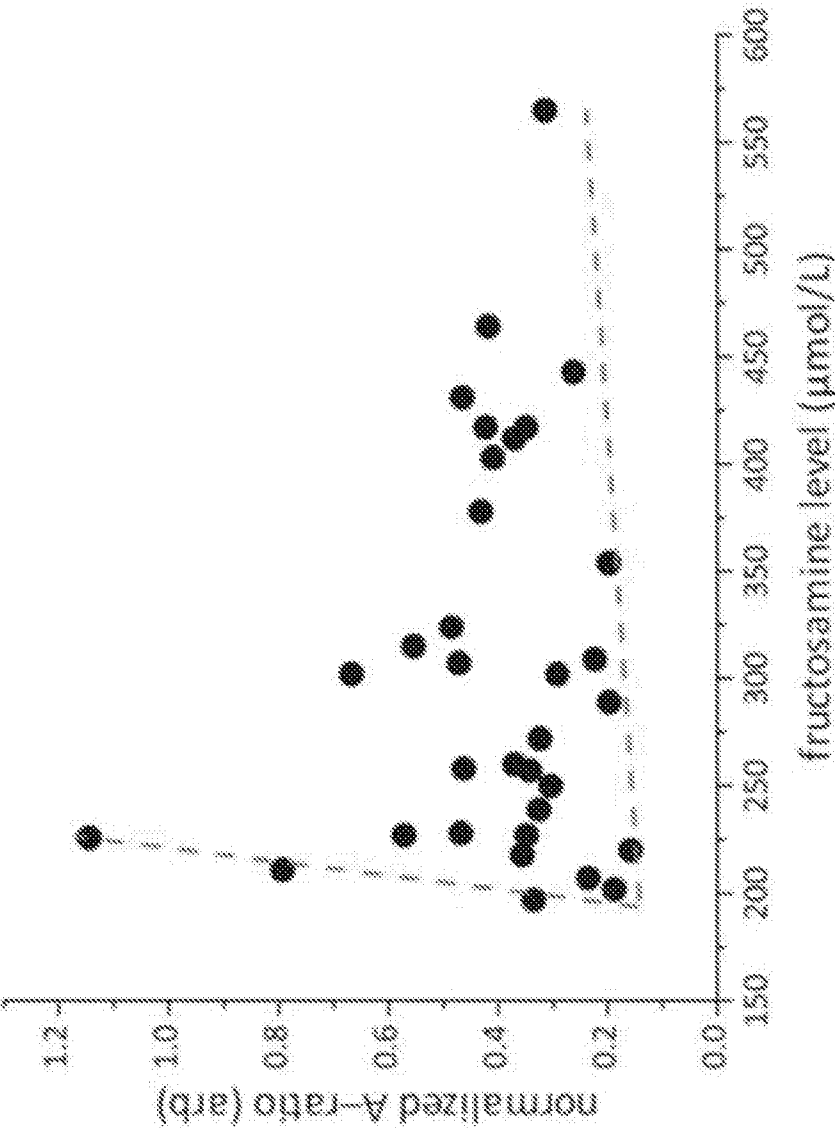


FIG. 16B

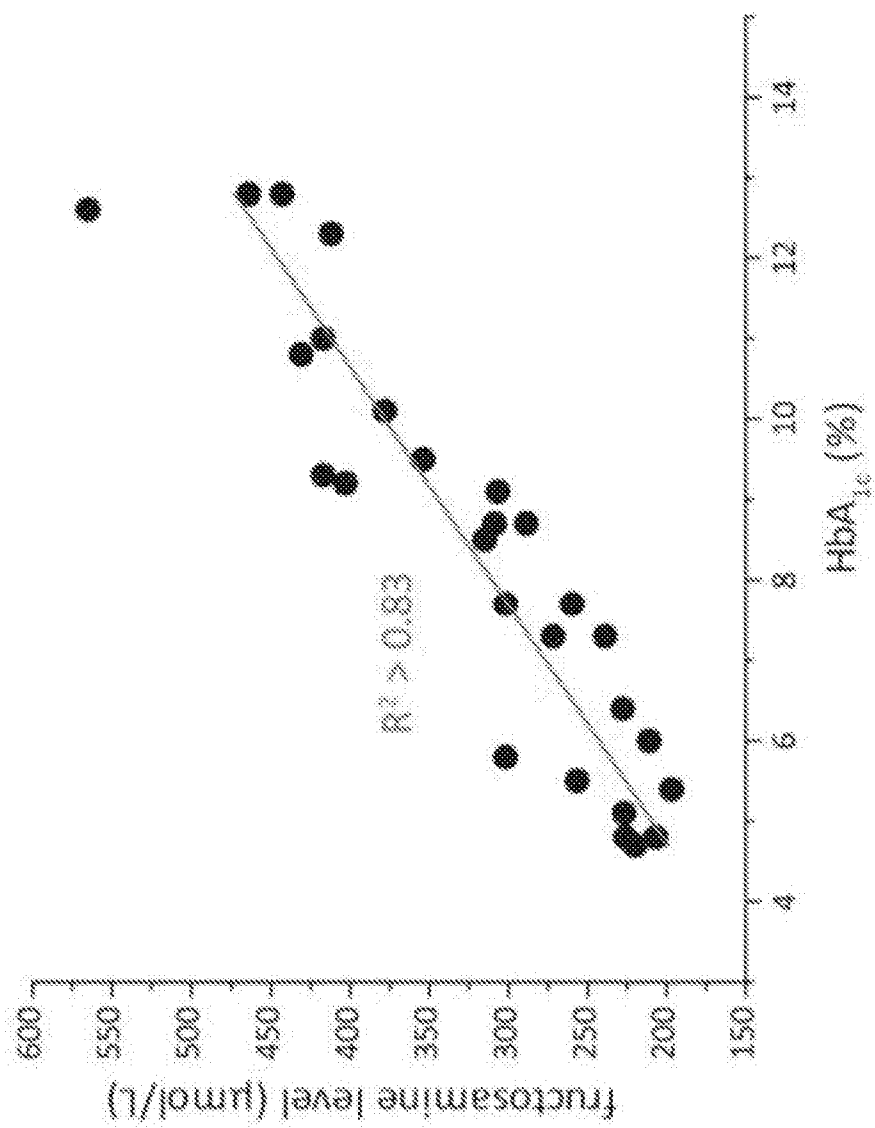


FIG. 16C

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US16/29075

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - A61B 5/055; G01R 33/20, 33/44, 33/48 (2016.01)

CPC - A61B 5/055; G01R 33/302, 33/448, 33/3808; G01N24/08

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC(8): A61B 5/055; G01R 33/20, 33/44, 33/48 (2016.01)

CPC: A61B 5/055; G01R 33/302, 33/448, 33/3808; G01N24/08

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

PatSeer (US, EP, WO, JP, DE, GB, CN, FR, KR, ES, AU, IN, CA, INPADOC Data); Google Scholar, Ebsco, IEEE

KEYWORDS: relaxometry, NMR, assessing, determining, studying, evaluating, measuring, redox, oxidation reduction reaction, state, position, condition, shape, monitor, observe, watch, see, view, disease, sickness, ailment, virus, infection, syndrome, illness, nitrosative

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X — Y	DE 2013 103 969 U1 (ASPECT IMAGING LTD) September 26, 2013; paragraphs [0002], [0013], [0071], [0074], [0087], [0089], [0097], claim 5, 6 & 9	1 & 7 — 2-6, 8-12, 26-29, 31-34
X — Y	US 2013/0273523 A1 (T2 BIOSYSTEMS, INC.) October 17, 2013; figure 1A, paragraphs [0104]-[0105], [0292] & [0333]	14 — 15, 16
Y	Edden, R et al. "Longitudinal and Multi-Echo Transverse Relaxation Times of Normal Breast Tissue at 3 Tesla", September 29, 2010 [retrieved 2016-06-27]; Retrieved from the Internet <URL: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3154635/ >. page 982, column 2, paragraphs 3 & 4, page 985, figure b, page 986, column 10, paragraph 3	2
Y	Farrow, N et al. "Characterization of the Backbone Dynamics of Folded and Denatured States of an SH3 Domain", October 10, 1996 [retrieved 2016-06-27]; Retrieved from the Internet <URL: http://www.ncbi.nlm.nih.gov/pubmed/9054544 >. page 2390, citation 1, page 2396, Table 1	3 & 26-29, 31-34
Y	WO 2012/118442 A1 (MASSACHUSETTS INSTITUTE OF TECHNOLOGY) September 07, 2012; page 4, lines 14-21, claim 1	4-6, 8 15, & 32-33
Y	US 5,674,692 A (BAEKESKOV, S et al.) October 07, 1997; claim 1	9
Y	US 2007/0238793 A1 (LOCKWOOD, S) October 11, 2007; paragraph [0081]	10, 12, 27, & 29



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent 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 when the document is taken alone

"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

Date of the actual completion of the international search

30 June 2016 (30.06.2016)

Date of mailing of the international search report

14 SEP 2016

Name and mailing address of the ISA/

Mail Stop PCT, Attn: ISA/US, Commissioner for Patents
P.O. Box 1450, Alexandria, Virginia 22313-1450

Facsimile No. 571-273-8300

Authorized officer

Shane Thomas

PCT Helpdesk: 571-272-4300
PCT OSP: 571-272-7774

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US16/29075

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 8,465,988 B2 (JENSEN, G) June 18, 2013; claim 1	11 & 28
Y	US 2006/0006865 A1 (ZHANG, X et al.) January 12, 2006; paragraph [0006]	6, 8, 16, 34
A	WO 2006/095238 A1 (WARNER-LAMBERT COMPANY LLC) September 14, 2006; claims 1 & 6-7	1-16 & 26-34
A	EP 1 595 573 B1 (DUKE UNIVERSITY) January 10, 2008; paragraph [0035]	1-16 & 26-34

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US16/29075

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

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

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
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, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

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

See extra sheet.

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☒ 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 claims Nos.:
1-16 and 26-34

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

-***-Continued from Box No. III Observations where unity of invention is lacking -***-

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fee must be paid.

Group I: Claims 1-16 and 26-34 are directed towards a method of monitoring a disease status and identifying a risk.

Group II: Claims 1-13, 17-25, and 35-36 are directed towards a method of assessing a redox state of a sample using a magnetic state diagram.

The inventions listed as Groups I-II do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons:

The special technical features of Group I include at least assigning a risk level to a subject based on a ratio of the longitudinal relaxation time and the transverse relaxation time, which are not present in Group II.

The special technical features of Group II include at least plotting a magnetic state diagram; and interpreting the state of the sample based on the location of the sample in the diagram, which are not present in Group I.

The common technical features shared by Groups I-II are measuring a longitudinal relaxation time and a transverse relaxation time in the sample using a magnetic resonance relaxometry device; and assessing a redox state of the sample from the longitudinal relaxation time and the transverse relaxation time of the sample.

However, these common features are previously disclosed by DE 20 2013 20103969 U to ASPECT IMAGING LTD. (hereinafter "Aspect"). Aspect discloses measuring a longitudinal relaxation time and a transverse relaxation time in the sample using a magnetic resonance relaxometry device (measuring a longitudinal relaxation time and a transverse relaxation time in a sample using a magnetic resonance apparatus (magnetic resonance relaxometry device); [0013], [0071], [0074], [0087] & [0089], claim 9); and assessing a redox state of the sample from the longitudinal relaxation time and the transverse relaxation time of the sample (and assessing an oxidation state (redox state) of the sample from the longitudinal relaxation time and the transverse relaxation time of the sample; [0013], [0071], [0074], [0087], [0089] & [0097]; claim 9).

Since the common technical features are previously disclosed by the Aspect reference, these common features are not special and so Groups I-II lack unity.