Team ID:_____

CHEMISTRY OF THE HUMAN BODY

(Sample Questions Key)
WUCT 2018

The three questions below are meant to give a sense of the kinds of questions that might be asked on the exam in April 2018. The actual exam is 60 minutes long, and it may differ in topic areas covered and difficulty. Necessary constants, equations, and conversions may be found on the last page of this document. Unless otherwise stated, explanations must be written in complete sentences, diagrams must be labeled, and units must be shown in calculations to receive full credit. Please answer the questions in the space provided. No work on the back of the sheets or attached sheets will be graded. The amount of points each question is worth will be indicated on the actual exam. Note that not all lone pairs are necessarily shown on every chemical structure.

Team Members:

1. _____   2. _____

High School: _____

HUMAN BODY

Team ID:_____

1. This question concerns a tetrameric (consisting of four subunits) protein, hemoglobin (abbreviated as Hb), that binds $O_{2(g)}$ and $CO_{2(g)}$ in our body. Each subunit of the hemoglobin protein contains a single heme B group (shown below). We will examine various properties of gases, and of the hemoglobin protein itself. Note that there is a ferrous iron (Fe^{2+}) at the center of each of the heme B group.
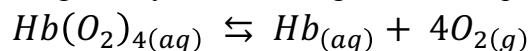

Heme B
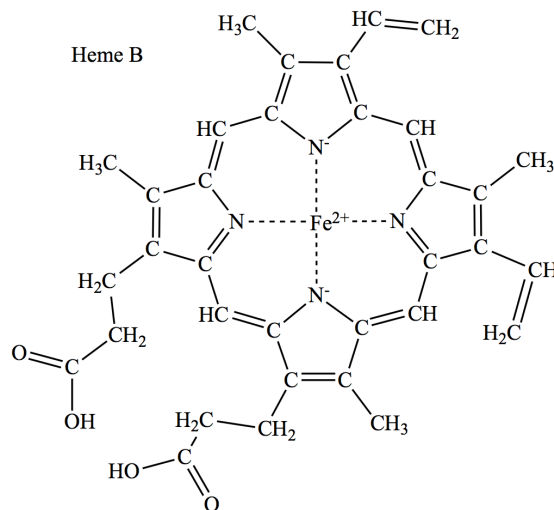
a. What is the oxidation state of *free*, molecular oxygen (not shown)?

   Answer: The oxidation state is zero because it is in its diatomic, natural state. This implies it has an oxidation state of zero.

b. What is the ground-state electron configuration of Fe(II)? Noble gas abbreviations may **not** be used.

   Answer: $1s^2\, 2s^2\, 2p^6\, 3s^2\, 3p^6\, 3d^6$; the $4s^2$ valence electrons from Fe^0 are lost first because the 4s orbital has a higher orbital energy than a partially or totally filled 3d orbital.

c. The equilibrium of dissociation with equilibrium constant K_d of oxygenated Hb, $Hb(O_2)_{4(aq)}$, is given by the following chemical equation:
$$Hb(O_2)_{4(aq)} \leftrightarrows Hb_{(aq)} + 4O_{2(g)}$$
   Where the equilibrium constant K_d is:
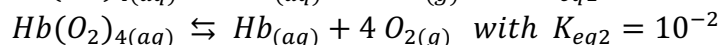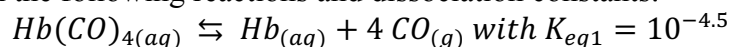$$K_d = \frac{pO_2{}^4\,[Hb]}{[Hb(O_2)_4]}$$

i.   While exercising, oxygen is consumed via a process called aerobic respiration. Assuming that equilibrium is established, and that the person is at rest, explain how the equilibrium would shift after the person runs ten miles.

Answer: By Le Chatelier's principle, the equilibrium would favor the right side. O_2 consumption by aerobic respiration drives the dissociation reaction forward.
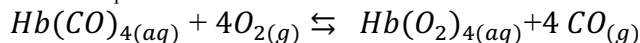
ii. Carbon monoxide gas ($CO_{(g)}$) exposure can lead to CO poisoning in humans, which can result in hypoxia and/or death. Draw Lewis structures below for both $CO_{(g)}$ and $O_{2\,(g)}$. Circle the Lewis structure of the molecule that you predict to have a stronger affinity for the Fe^{2+} of the heme B group shown on the first page.

Answer: the two Lewis structures are shown above. The carbon monoxide should be circled because it has a much higher affinity for heme b than oxygen does. This is partly due to the dipole moment of carbon monoxide, but also due to the interaction between an unfilled antibonding orbital on carbon monoxide interacting with a filled D orbital on the ferrous atom. The oxygen does not have these interactions, and it consequently has a lower affinity for the heme group. **students are not expected to have this level of chemical intuition**

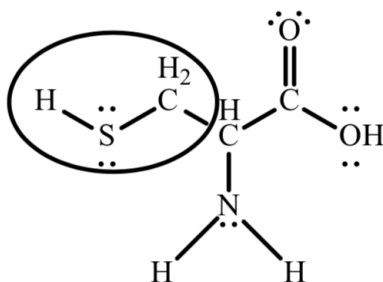iii. Given the following reactions and dissociation constants:
$$Hb(CO)_{4(aq)} \leftrightharpoons Hb_{(aq)} + 4\,CO_{(g)} \; with \; K_{eq1} = 10^{-4.5}$$
$$Hb(O_2)_{4(aq)} \leftrightharpoons Hb_{(aq)} + 4\,O_{2(g)} \; with \; K_{eq2} = 10^{-2}$$
Calculate the $K_{eq.}$ of the reaction:
$$Hb(CO)_{4(aq)} + 4O_{2(g)} \leftrightharpoons Hb(O_2)_{4(aq)} + 4\,CO_{(g)}$$
Answer: In order to obtain to the K_{eq} of the third equation, the order of equation 2 must be reversed, so the K_{eq-2} will be the inverse of K_{eq2}.
From there, the two equations can be added together to obtain the final equation 3. In order to find the K_{eq} of equation three, the K_{eq}'s of the coupled reactions must be multiplied. So $K_{eq3} = K_{eq1} * (1 / K_{eq2}) = K_{eq3} = K_{eq1} * K_{eq-2}$. The final answer is $10^{-2.5}$.

2. Proteins serve many essential roles in the body including cell signaling, cell structure, and cellular transport. This question will explore some ways in which proteins interact with themselves and others in order to perform their respective functions.

     a. This question part will concern the intermolecular forces that are involved in some protein structures. One of the common structural aspect of proteins is the β-sheet. Shown below are protein strand 1 and protein strand 2, which are part of a β- sheet. This diagram will be referenced parts i and ii of this question.

         i. Name the dominant intermolecular interaction that occurs between Strand 1 and Strand 2.

Answer: Hydrogen bonds, hydrogen bonding (either is acceptable).

         ii. On the figure above, draw straight, dashed lines (- - - - -) between the pairs of atoms participating in each interaction you indicated in part i.

Answer: See dashed lines indicating hydrogen bonding pairs on diagram   above.

     b. While most amino acids interact through intermolecular forces, cysteine (shown below) is unique in that is can form a covalent bond with another cysteine. This disulfide bond is essential in many protein structures. For the purposes of this question, consider the R group (circled below) of cysteine to be polar.

i. Is the reaction below to form a disulfide bond a reduction or oxidation? Justify your reasoning.
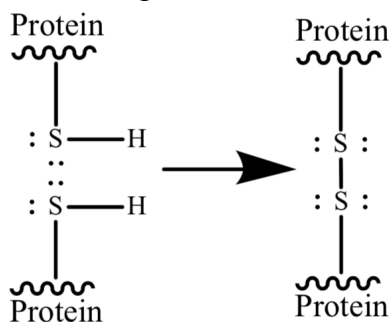
Answer: Oxidation. Justification: sulfur loses electrons, or showing 2 e- and 2 H+ on the product (right) side of the reaction.

c. Consider peptide strand N which is the normal structure of this protein, and strand M which is a mutant because the two outermost circled groups have been changed. The full structures are shown below.
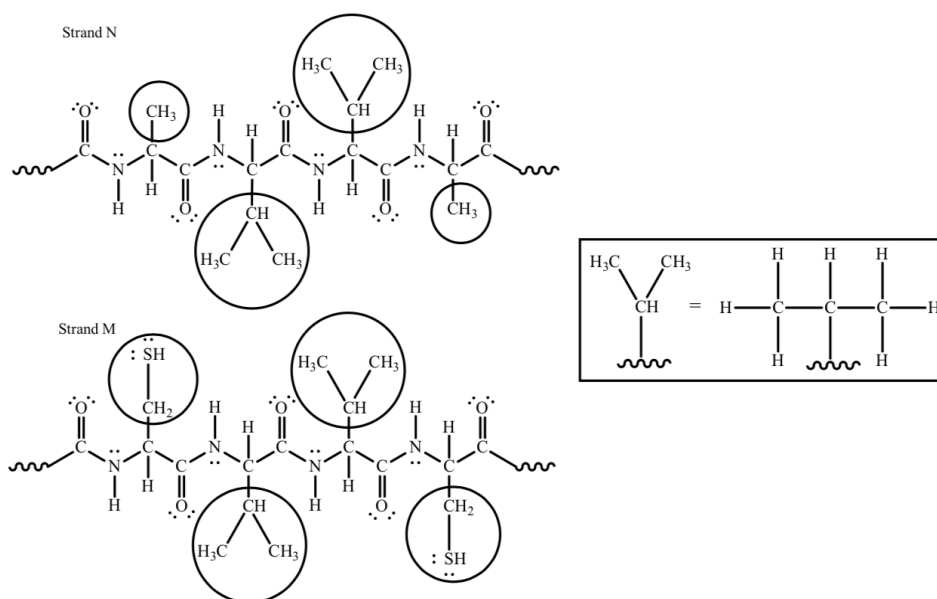
i.   Strand N is typically found within the interior of the cellular membrane, in between the lipid bilayer, where there is *no* water. Why might it be more favorable for strand M to be in the aqueous environment of the cytoplasm? Complete answers will analyze the circled groups of each strand.

Answer: Strand M has two polar amino acids (cysteines) in place of its native hydrophobic amino acids (alanines). This would make it less favorable for strand M to reside in the hydrophobic interior of the cell membrane. Students are not responsible for naming the amino acids.

ii.   Suppose strand M is able to flex and fold about its bonds. Propose a model for how this peptide might bond in order to minimize the hydrophilic interactions so that it is more favorable to remain in a hydrophobic environment. Models may be a diagram (not all atoms need to be included) or written description, and they should include relevant interactions and bonds.
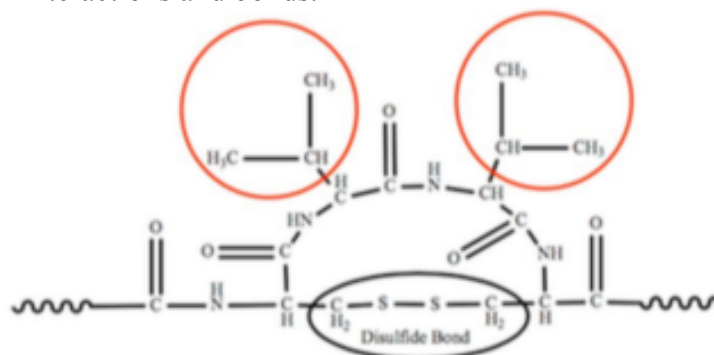
Answer: See diagram, not all atoms need to be shown; however, the circled disulfide bond needs to be explicitly written out, as it is the key bond formed. For example, it would be acceptable to write *-CH_2- S-S- CH_2- * with a line connecting the *'s in a ring-like fashion. Note that not all lone pairs are shown and that not all angles and bond lengths are accurate. The key concept is that the two -SH groups form a bond which forms a ring structure. The red circles are for the following part iii.

iii. Consider the orientations of the middle two circled groups, -$CH(CH_3)_2$. How will these two groups be oriented so that the bonding interaction in part 2cii (previous question part) will occur? Diagrams and/or written explanations may be used.

Answer: See red circles in diagram above for a visual representation. The -CH(CH3)2 groups are very large, and they will be oriented towards the outside of the of the newly formed ring structure. This minimizes the space that they take up on the inside of the ring, so the distance between the two -SH groups in minimized, which is required for the initial bonding to occur between the two -SH groups.

3. The body must be able to maintain a wide range of pH values in various areas of the body. For example, the pH of blood is 7.35, the pH of the stomach ranges from 1.5 to 3.5.

   a. Many body systems use buffer systems to maintain their optimal pH. Using the equation of a weak acid dissociation show below, derive the Henderson-Hasselbalch equation as it is shown below. Include all intermediate steps.

$$HA \leftrightarrows H^+ + A^-$$

Answer: $Ka = [H+][A-] / [HA]$

$[H+] = Ka [HA] / [A-]$

$-\log[H+] = -\log[Ka] - \log ([HA] / [A-])$

$$pH = pK_a + \log \frac{[A^-]}{[HA]}$$

   b. The Phosphate Buffer system plays an important role in buffering renal tubular fluid and other intracellular fluids to additions of strong acids and bases. At physiological pH, the predominant species of this system are $H_2PO_4^-$ and its conjugate base, HPO_4^{2-}. The other species of this polyprotic system, such as H_3PO_4 and PO_4^{3-}, can be ignored. If a solution consists of 35.3 mM HPO_4^{2-} and 2.3mM $H_2PO_4^-$, what is the pH? (Hint: The pKa of $H_2PO_4^-$ is 7.21).

   Answer: $pH = pKa_{H2PO4-} + \log ([HPO_4^{2-}]/[H_2PO_4^-])$

   $pH = 7.21 + \log(35.3\ m M /2.3\ m M)$

   $pH = 7.21 + 1.19$

   $pH = 8.40$