

# Maria vs Malaria

## Understanding the molecular basis for treatment of malaria via a competitive inhibition of *Plasmodium Falciparum* Lactate Dehydrogenase

### CASE CONTEXT

#### *Learning Objectives for this section:*

- Explain the cause of malaria and evaluate the current status of the malaria epidemic
- Identify where Malaria cases are most prominent and which demographics are at risk of contracting Malaria
- Describe how rapid diagnostics test (RDT) for Malaria works.
- Discuss how RDT and adequate treatment of Malaria can improve patient health

Maria is a 35 year old Environmental scientist from New York City, and was excited for her trip to the Amazon Rainforest! During her trip she went hiking, and camped in various parts of rural Brazil to do research on a rare species of Red-Eyed Tree Frogs, which dwells in warm wet swamps of the rainforest. After three weeks of research in Brazil, she returned to the States to prepare for her research symposium where she would share her findings! About a week after her return, Maria began to feel very sick, with a high fever and other flu-like symptoms.

### Diagnosing Maria:

Suspecting that she contracted malaria when she was in Brazil, Maria took a Rapid Diagnostic Test (RDT). Rapid Diagnostic Test (RDT) is a very powerful technique that allows a fast diagnosis of certain disease causing pathogens in the body usually in 20 minutes or less without the need for sophisticated instrumentation. It is low-cost, simple to operate and read, sensitive, specific, stable at high temperatures, and works in a short period of time. Rapid tests are most often used to diagnose infectious diseases including flue, strep throat, HIV, Covid 19, and Malaria. Rapid tests are also used in certain home-based tests, such as pregnancy tests.

Maria used the RDT for Malaria shown in Figure 1) that detects the presence of specific malarial antigens in blood specimens including the histidine-rich protein II (HRP-II), aldolase, and **parasite lactate dehydrogenase (pLDH)**. It is based on immunoassay principles and you can learn the details of how the test works [here](#). You can also watch a field application of this RDT for Ugandan patients [here](#).



Figure 1: The BinaxNOW™ Malaria test (Abbott) (<https://www.globalpointofcare.abbott/en/product-details/binaxnow-malaria.html>)

Upon taking the test, Maria tested positive for malaria and went to the hospital. Her doctors requested extra blood tests that identified the malaria parasite she carried the *Plasmodium falciparum*, a parasite found in the bite of a female mosquito with malaria.

As the doctors were discussing which treatment would be best for Maria, she decides to learn more about this disease to be an informed participant in her own healthcare.

## Understanding Malaria

Why is malaria one of the most common infectious diseases in the world, with nearly 247 million cases worldwide in 2021 with 619 000 deaths?

Read this brief list of [key malaria facts](#) from the World Health Organization and watch [this video](#) to learn about what causes malaria and how it infects people. (Additional resources: CDC: <https://www.cdc.gov/parasites/about.html>)

**REVIEW QUESTIONS:** (Formatted for autograding, can also be given as free response)

- 1) Which of the following five *Plasmodium* (single-celled parasites) species is the deadliest malaria parasite and the most prevalent on the African continent? most intense malarial infection in humans?**
  - a. *Plasmodium vivax*
  - b. *Plasmodium malariae*
  - c. *Plasmodium falciparum*
  - d. *Plasmodium ovale*
  - e. *Plasmodium knowlesi*
  
- 2) What are some of the symptoms of this disease? Choose all that apply.**
  - a. Fever
  - b. Cough
  - c. Vomiting
  - d. Nausea
  - e. Headache
  - f. Rashes
  
- 3) Which demographics are most susceptible to it?**
  - a. Children under 5 years old
  - b. White males
  - c. Pregnant women
  - d. HIV/AIDS patients
  
- 4) Prevalance: In what regions is malaria most prevalent, and what do they have in common?**

Malaria is most prevalent in \_\_\_\_\_ regions, especially after the rainy season that provides stagnant \_\_\_\_\_, such as puddles, for *anopheles* mosquitoes to breed in.

- 5) Malaria transmission to humans: The figure shows the lifecycle malaria plasmodium. Match the listed lifecycle steps with the numbers shown on the figure.

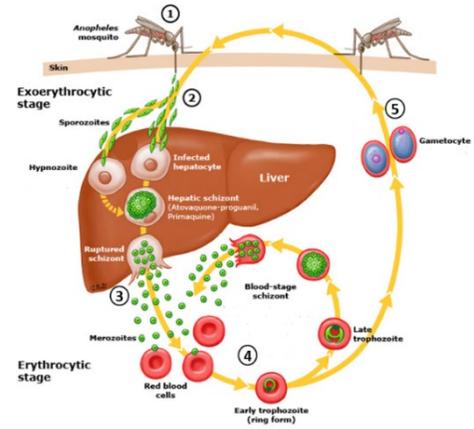


Figure 2: **Malaria plasmodium lifecycle** adapted from [https://www.uptodate.com/contents/image?imageKey=ID%2F70176&topicKey=ID%2F5722&source=see\\_link](https://www.uptodate.com/contents/image?imageKey=ID%2F70176&topicKey=ID%2F5722&source=see_link)

- (1) *Plasmodium*-infected *Anopheles* mosquito bites a human and transmits sporozoites into the bloodstream.
- (2) Sporozoites migrate through the blood to the liver where they invade hepatocytes and divide to form multinucleated schizonts (pre-erythrocytic stage).
- (3) The schizonts rupture and release merozoites into the circulation where they invade red blood cells.
- (4) Within red cells, merozoites mature from ring forms to trophozoites to multinucleated schizonts (erythrocytic stage).
- (5) Some merozoites differentiate into male or female gametocytes. These cells are ingested by the *Anopheles* mosquito and mature in the midgut, where sporozoites develop and migrate to the salivary glands of the mosquito.

**Or: Describe the lifecycle of malaria plasmodium:**

## GETTING TO THE STRUCTURE:

### *Learning Objectives for this section:*

- Describe the function of LDH in glucose metabolism.
- Describe the reaction LDH catalyzes including the substrates, products, and cofactors of this reaction.
- Describe the significance of anaerobic respiration in parasites
- Discuss how LDH can be used as a drug target to treat malaria

### Meet Michaelangelo:

Upon learning about her malaria diagnosis, Maria frantically called Michaelangelo, a colleague of hers at the CDC. She was worried that she wouldn't be able to present her findings at the upcoming research symposium! Being also a close friend to Maria, Michaelangelo agreed to do some research on the *Plasmodium falciparum*, taking special interest in how the parasite is able to multiply so rapidly.

As a part of his job, he was aware of the diagnostic usage of the serum levels of numerous enzymes for a variety of human conditions. The presence of enzymes normally confined to specific tissues or organs in the serum indicates that cellular damage has occurred resulting in the release of intracellular components into the blood. For example, when a physician orders an assay for liver enzymes, the purpose is to ascertain the potential for liver cell damage. Since Maria's RDT indicated the presence of malarial parasite Lactate Dehydrogenase (LDH) enzyme in Maria's blood, he decided to focus on understanding the role of LDH in malarial parasite survival and as a possible treatment target.

### **Role of Lactate Dehydrogenase in Energy Metabolism:**

Adenosine triphosphate (ATP) is an organic compound and hydrotrope that provides energy to drive many processes in living cells, such as muscle contraction, nerve impulse propagation, condensate dissolution, and chemical synthesis. All known forms of life, including aerobic and anaerobic organisms require ATP for survival and hence ATP is often referred to as the "molecular unit of currency" for intracellular energy transfer.

Glycolysis is a central pathway in carbohydrate metabolism that converts glucose into pyruvate and produces ATP along the way.  $\text{NAD}^+$  is a required cofactor for some of the enzymes in this pathway and is reduced to NADH while glucose is oxidized to pyruvate. Pyruvate that is formed as the product of this conversion has a few different paths it can follow. For organisms that require large amounts of energy (ATP) to function the predominant pathway is the "aerobic respiration" for which pyruvate is converted into acetyl-CoA and channeled into the Krebs cycle. For organisms that rely on "anaerobic respiration" other pathways are needed to avoid buildup of pyruvate and replenishment of glycolytic cofactors to continue ATP production through glycolysis.

Lactate dehydrogenase (LDH) is the gatekeeper enzyme for lactic acid fermentation, one of the main alternative pathways for pyruvate and NADH recycling. It catalyzes the spontaneous conversion of pyruvate to lactate and requires NADH as the cofactor.

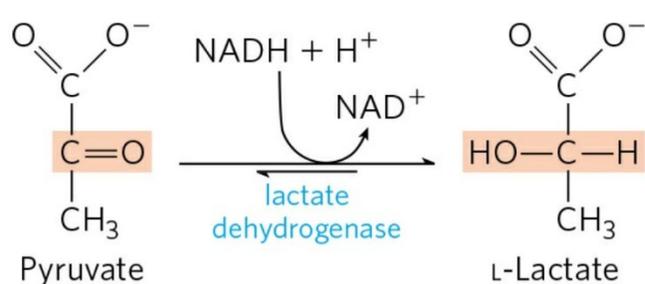


Figure 3: Lactate dehydrogenase (LDH) catalyzed reaction of the reversible conversion of pyruvate to lactate. This is a redox reaction where the cofactor NADH gets oxidized to  $\text{NAD}^+$  as pyruvate is reduced to lactate.

Because LDH is essential in the breakdown of pyruvate into lactate under anaerobic conditions, and recycling of  $\text{NAD}^+$  for continual glycolysis, it is no surprise that LDH must be present in most living organisms that utilize glycolysis for ATP production.

Through his research Michaelangelo learned that during erythrocyte stages of its life cycle, the *Plasmodium falciparum* parasite produces its energy mainly through glycolysis followed by lactic acid fermentation.

**Q1. The malaria parasite is a protozoan, a eukaryotic organism. How is the predominant pathway for ATP generation in Malaria parasites differ from most other eukaryotic organisms? How can this difference be leveraged for disease treatment?**

# EXPLORING THE STRUCTURE

## Learning Objectives for this section:

- Use Uniprot and PDB to find specific sequences and structures of for *Plasmodium falciparum* and human LDH
- Use Bioinformatic tools ProtParam and Align, and the visualization tool Mol\* to explore and compare parasite LDH and human LDH.
- Locate the active site of LDH and its coenzyme NADH/NAD<sup>+</sup> in the active site.
- Identify the different types of interactions between the coenzyme and the surrounding residues in *pf*LDH and *h*LDH
- Compare and contrast the *pf*LDH and *h*LDH active site structures

## Michaelangelo calls Maria:

Much to Maria's surprise, she receives an eager call from Michaelangelo. He tells her about the metabolic significance of LDH in the *P. falciparum* and how its inhibition could be used to combat malaria. She is ecstatic about this, but then confused. Don't humans have LDH too? She remembers reading that levels of lactate dehydrogenase (LDH) in serum is especially diagnostic for myocardial infarction. Wouldn't the inhibition of the *pf*LDH consequently inhibit her own human LDH? She shares this concern with Michaelangelo who reassures her that inhibiting the *pf*LDH is a safe and effective way to treat malaria. He tells her that to understand why, she needs to gain a molecular understanding of how LDH works based on its structure. Maria gets to work.

## Exploring the primary Structure of *Plasmodium falciparum* LDH (*pf*LDH) and human LDH (*h*LDH):

1. Go to <http://www.uniprot.org>
2. In the search field, enter "*Plasmodium falciparum* LDH" and choose the table view to view results.
3. Find the entry for for full length *Plasmodium falciparum* with the Protein Name: **L-lactate dehydrogenase** and entry name: **LDH\_PLAFD** and check the box left of the entry ID.
4. Once checked, find the tab "add" with a basket icon above the top banner and click it to add this protein sequence to the basket.

Entry	Entry Name	Protein Names	Gene Names	Organism	Length
<input checked="" type="checkbox"/> Q27743	LDH_PLAFD	L-lactate dehydrogenase[...]		Plasmodium falciparum (Isolate CDC / Honduras)	316 AA
<input type="checkbox"/> P13774	LDH_PLAFA	L-lactate dehydrogenase[...]		Plasmodium falciparum	42 AA

5. Click on the entry ID next to the checked box and scroll down to the "Sequence" section of the file that opens up (almost at the end) and "copy sequence".

Sequence

Tools - Download - Add - Highlight - Copy sequence

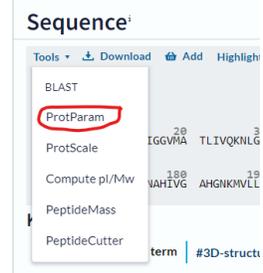
Length 316  
Mass (Da) 34,108

Last updated 1996-11-01 v1  
Checksum: D25EB5639548BFC1

MAPKAKIVLV 10 GSGMIGGVNA 20 TLIVQKILGD 30 VVLFDIKQNI 40 PHGKALDTSH 50 TMMHAYSNCK 60 VSGSHTYDDL 70 AGADVIVTA 80 GFTKAPGKSD 90 KEHRDOLLP 100 LNKKIMEIIG 110 GHIKKKCPNA 120 FIIIVTNPVD 130 VHVQLHQHS 140 GVPKIKIIGL 150 GGLDTSRLK 160  
YYISQKLIVC 170 PRDVNHHVIG 180 AHGKHKVLLK 190 RYITVGGIPL 200 QEFINNKLI 210 DALEALFDR 220 TVNITALEIVN 230 LHASPYVAPA 240 AATIEMAESY 250 LKDLKKVLLC 260 STLLEGQVGH 270 SDIFGGTPVV 280 LGANGVEQVI 290 ELQINSEEKA 300 KFDEATAETK 310 RPKALA

**Q2. Paste the *pf*LDH sequence below. Make sure to include the Uniprot Entry ID # and the name on top of the sequence**

6. Click the “Tools” dropdown menu and select **ProtParam**.
7. Click submit at the bottom of the page that opens to run the analysis using the entire protein sequence.



**Q3. Using the displayed results fill in the following information.**

*P. falciparum* LDH (*pf*LDH) with the Protein Accession # Q27743 has \_\_\_\_\_ number of amino acids and has a molecular weight of \_\_\_\_\_ Da. Its predicted pI is \_\_\_\_\_. It has \_\_\_\_\_ negatively charged amino acids and \_\_\_\_\_ positively charged amino acids at physiological pH.

Unlike *P. falciparum* that has a single gene coding for a single polypeptide used to form its functional LDH (*pf*LDH), humans have two different genes that code for two different polypeptides (*h*LDH-A and *h*LDH-B) that can be used to assemble a functional *h*LDH. We will look at the formation of these assemblies (quaternary structure of LDH) in a later section. For now let's repeat the same exercise above, to obtain information on *h*LDH-B.

8. Go back to the Table list of results you received after step 2 above and enter “human LDH” on the search bar at the top of this page.
9. Find the entry for human with the Protein Name: **L-lactate dehydrogenase B chain**, Entry Name: **LDHB\_HUMAN** and check the box left of the entry ID.
10. Repeat steps 4-8.

**Q4. Paste the *h*LDH-B sequence below. Make sure to include the Uniprot Entry ID # and the name on top of the sequence.**

**Q5. Using the displayed results fill in the following information.**

Human LDHB (*h*LDHB) with the Protein Accession # P07195 \_\_\_\_\_ has number of amino acids and has a molecular weight of \_\_\_\_\_ Da. Its predicted pI is \_\_\_\_\_. It has \_\_\_\_\_ negatively charged amino acids and \_\_\_\_\_ positively charged amino acids at physiological pH.

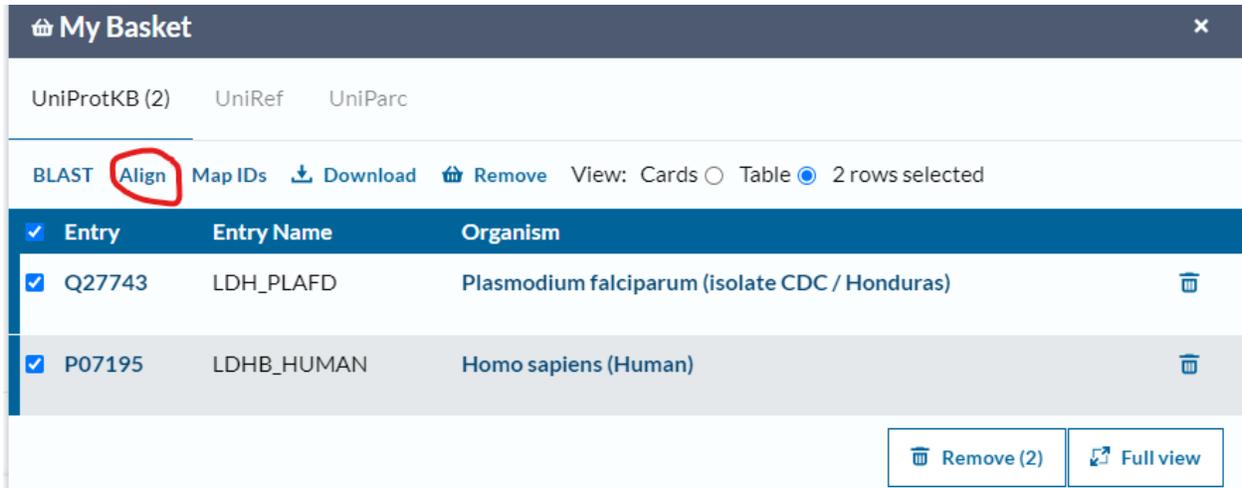
Now that we have compiled some basic physicochemical information for these two protein sequences (one from the parasite and one from humans) let's compare them to one another to determine similarities and differences that might shed light to their biological functions.

**Q6. Compare and contrast the total charges of *pf*LDH and *h*LDH-B. What is the overall charge difference between them?**

Uniprot also allows us to align protein sequences to compare the similarities and differences between them at each amino acid location along the sequence. To do this go to your “basket” on the upper right corner of your Uniprot main page.



11. Select the two sequences for pfLDH and LDH-B in the basket and click “Align” above the banner.



12. Enter “pfLDH vs hLDH-B” as the name for your align job in the box below the sequences and click align on the right bottom corner of the page.

13. Once the alignment is completed, click on the word “completed” under “status” column.

**Q7. Take a screenshot of the displayed alignment and paste below.**

14. Using the two pull down menus “highlight properties” and “Select Annotation” explore the similarities and differences in physicochemical, structural, and functional aspects of these two sequences.

**Q8. Based on your findings which same amino acid do both pfLDH and hLDH-B contain at their binding site? What is the residue number for this active site residue for the pfLDH sequence?**

**Q9. List some of the similarities and differences you identified between these two proteins based on their primary structure below.**

**Q10. Using only the primary structural information you obtained so far, what can you infer about the similarities and differences between pfLDH and LDH-B, in the context of glycolysis? How might these differences affect the enzyme’s catalytic ability?**

## ***Exploring the higher order structure of LDH using PDB and Mol\*:***

Now that we have had the opportunity to explore the primary structures of *pf*LDH and hLDH-B, we are prepared to analyze the differences in their **higher order structures**. In this section, we will start by exploring the three dimensional structural information for biologically active LDH molecules hosted in the Protein Data Bank (PDB), and use Mol\* to visualize the different protein structures to assess the conservation of structural features between the *Plasmodium falciparum* lactate dehydrogenase (*pf*LDH) and human LDH (*h*LDH).

- 1) Go to the RCSB Protein Data Bank (<https://www.rcsb.org/>). In the query box at the top of the webpage, input “LDH” and click search to explore various lactate dehydrogenases among organisms.
- 2) To explore *pf*LDH narrow your search by clicking Plasmodium falciparum under “Specific Name of Source Organism” list on the left and then clicking the green arrow at the very bottom of that menu.
- 3) Find the entry with the PDB ID 1T2C and click on it. This will be the structure we will be using to explore *pf*LDH.
- 4) On a NEW tab repeat step 1 and narrow your search to select LDH structures for “Homo Sapiens”
- 5) Find the entry with the PDB ID 7DBK and click on it. This will be the structure we will be using to explore hLDH.

You will be flipping between these two structures throughout your explorations so make sure to keep these two tabs separate on your browser.

**Q11. Use the information presented on the structure summary page for each structure to fill out the following table.**

**Table 1:** PDB summary at a glance for 1T2C, and 7DBK

<b>PDB ID</b>		
<b>Description</b>		
<b>Organism(s)</b>		
<b>Structure of the biological assembly</b> You can find this info under the “Biological Assembly” section on the upper left in the “global Stoichiometry” subheading		
<b>UniProt ID#</b> You can find this info in the “macromolecules” section under UniProt subheading.		

<b>Names and formula of ligands present in the structures</b>		
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You can find this under the “small molecules” section following the “macromolecules” section.

- 6) Click on the “3D View” tab next to the “Structure Summary” tab at the top to reach the 3D crystal structure of the “biologically functional” LDH.



3D structural analysis view offers us several resources to visualize the protein structure and its interactions with other biological partners, such as ligands. These could be any molecule including substrates, cofactors, and inhibitors.

On the top of your screen you will see the sequencing information of the protein and on the right-hand side is structural information as well as analysis tools you can use.

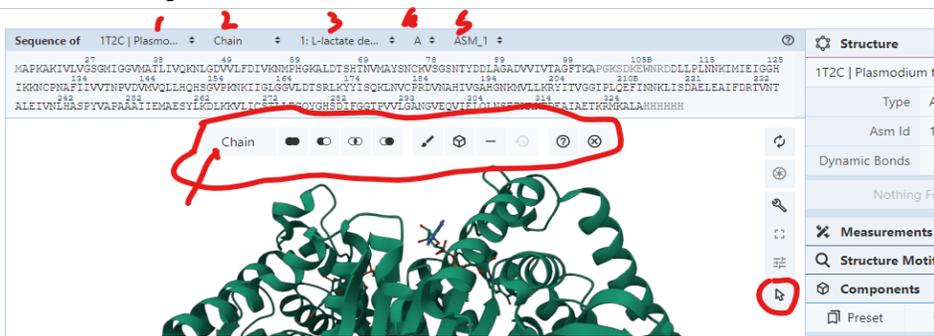
- 7) To make the visualization cleaner, under the “components” panel on the right, hide water (click on the “eye” icon).
- 8) Click and drag your mouse to see the molecule from different angles. Translate by pressing the right mouse button and moving or use Control + the left mouse button and move. Scroll in and out to zoom. You can always reset the program with the refresh icon at the top right.
- 9) Rotate the molecules around to obtain a relatively similar view for pfLDH and hLDH.

**Q12. Insert a screenshot of the displayed structures below, making sure to include the PDB ID# for each screenshot.**

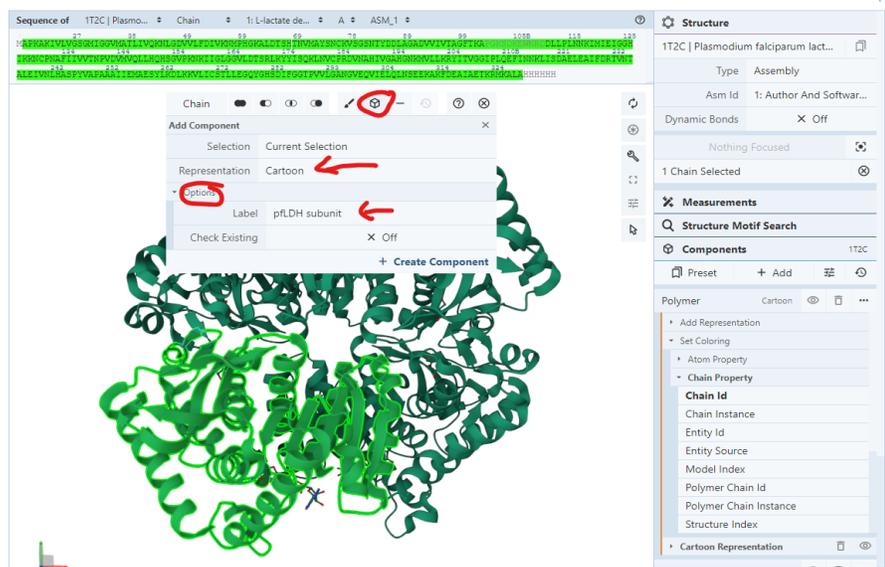
**Q13. Based on the 3D structures displayed, what is the quaternary structure of functional LDH in Plasmodium falciparum vs homo sapiens? What do their quaternary structures tell you about the number of active sites in the functional LDH molecule for each species?**

**Visualizing the structure of individual LDH subunits from pLDH (1T2C) and hLDH (7DBK) using Mol\*:**

10) Click on the selection tool on the Mol\* Viewer canvas which brings up an additional selection panel on the canvas above the displayed structure. Switch the leftmost selection criteria to “Chain”. Make sure that the topmost blue banner information is set to the first option for each of the five options as shown below.



11) Scroll and click on the displayed sequence which should highlight both the sequence and the corresponding subunit structure on the canvas. Then click on the “cube” icon to create a stand-alone object for this selected subunit. Change the “Representation” to cartoon and under options give the object a name you can remember (ex. pLDH subunit). Then click “Create component”.



12) This new object should now appear as a separate entity in the “Components” panel (below water)

- 13) Hide all other components (toggling off the eye icon next to them) leaving only the subunit visible. Click on an empty space on your canvas to clear out the selection. Now you should be only looking at a single subunit of your chosen LDH.
- 14) In the sidebar under **Components**, find “**pfLDH subunit**,” click the **3 dots** symbol to the right of “your subunit,” then click “**Add Representation**” to see a dropdown menu of options. Explore the different methods by clicking on one (eg: Ball & Stick). This will close the menu and add the visualization.  
 Components → pfLDH subunit (3 dots) → Add Representation → Ball & Stick
- 15) To show, hide, or delete a representation, click the **3 dots** symbol to the right of “Polymer” again and adjust the **trash** or **eye** symbols until only the **cartoon** representation is visible.  
 Components → pfLDH subunit (3 dots) → Add Representation → Cartoon
- 16) Now color your subunit, by *secondary structure* by going back to “your subunit” **3 dots** symbol, clicking “**Set Coloring**” to open the dropdown menu, selecting “**Residue Property**,” then “**Secondary Structure**.” (You may need to scroll to see all the options.)  
 Components → pfLDH subunit (3 dots) → Set Coloring → Residue Property → Secondary Structure
- 17) Repeat steps 3-9 on the other LDH molecule.
- 18) Rotate the molecules around to obtain a relatively similar view for pfLDH and hLDH subunits

**Q14. Insert a screen capture of both subunits colored by secondary structure below.**

**Q15. How do the secondary structural elements compare between pfLDH and hLDH-B subunits? How about the overall 3D fold of each subunit?**

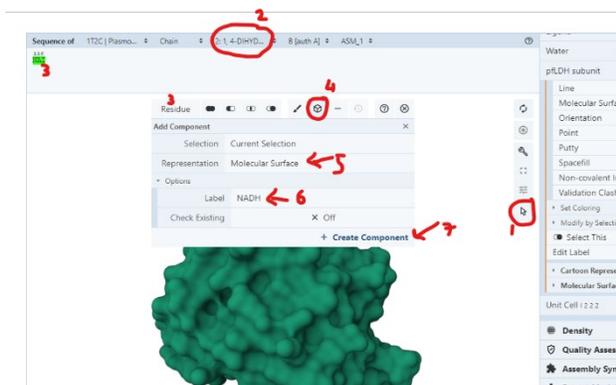
### ***Exploring the LDH active site:***

#### ***NADH Binding site:***

Now that we have a fairly good idea about the overall structural features of each LDH subunit, let’s visualize the location of the active site with respect to the rest of the LDH subunit structure for both *pfLDH* (1T2C) and *hLDH-B* (7DBK). **NADH** is a cofactor of LDH that binds to the enzyme at the active site. So we will start by visualizing NADH within the LDH subunit.

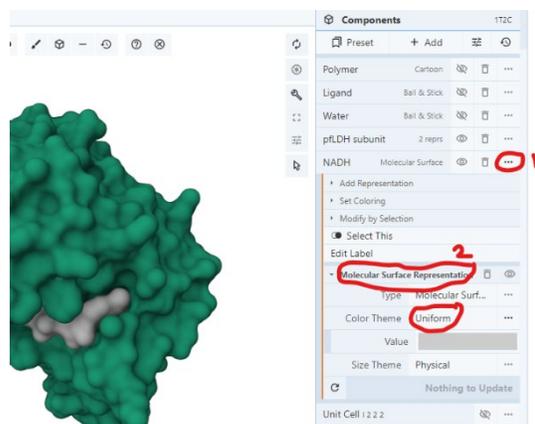
- 1) Go back to each of your pfLDH subunit structure tab and display it using a **surface representation**  
 Components → pfLDH subunit (3 dots) → Add Representation → **Molecular Surface**
- 2) In the blue bar above the sequence, following “Sequence of” change the third text box to **NAI** (1,4-DIHYDRONICOTINAMIDE ADENINE DINUCLEOTIDE), the second option.
- 3) To the left of the sidebar, click the **arrow** symbol at the bottom of the tool icons to bring up a toolbar. The first text option can be set to “**Residue**” or “**Chain**” and click on the sequence, “NAI”, to select it.

- 4) To add NAI as a component, click the **cube** symbol in the toolbar, click “<Create Later>” to change the representation to “**Molecular Surface.**” Add a label to identify the cofactor by clicking “Options” and entering “**NADH**” next to “Label,” then “**Create Component**” to finish the action.



- 5) After you complete this step you should see a new component called NAD on your left panel.

- 6) To change the color of the NADH, click the **3 dots** symbol to the right of your new “NADH” component in the sidebar and click on “**Molecular Surface Representation**” to bring up more customization options. Multiple choices for the Color Theme will allow you to clearly differentiate the cofactor from the protein, play around with multiple options then choose one. Example: Uniform



This should give you a view of the active site with the NADH cofactor. You may need to turn your molecule around to see the NADH.

- 7) Repeat steps 1-6 on the other LDH molecule.  
8) Rotate the molecules around to obtain a relatively similar view for pFLDH and hLDH NADH binding site.

**Q16. Insert a screen capture of both subunits showing NADH in the active site below.**

**Q17. Do you observe any differences in the NADH binding between the two LDH subunits in their respective active sites?**

### ***LDH active site residues***

- 9) Change the representation of NADH molecule to “Ball & Stick”

Components → pFLDH subunit (3 dots) → Add Representation → **Ball & stick**

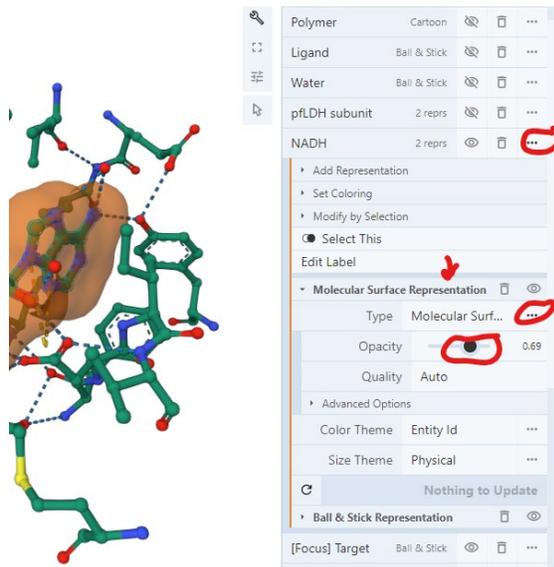
You will need to “hide” the molecular representation (toggle off the eye icon) to view only the ball and stick representation.

- 10) Turn off the Selection Mode by clicking the **arrow** symbol or the **x** symbol on the right side of the toolbar.
- 11) Focus on the ligand by clicking on to highlight it and zoom into its location.

Under “**Components**” there should be a tab titled “Focus: Surrounding 5A.” This shows the nearby residues and interactions within a 5 angstrom distance from the selection.

- 12) Clean up the visualization by hiding the rest of the LDH subunit structure. In the sidebar click the eye symbol next to all components except for NADH and the [Focus] elements.

- 13) Since there are multiple residues visible, it can be difficult to see the NADH. You can unhide the molecular surface representation for NADH and adjust its opacity and color to create an envelope around the cofactor.



The dash lines shown indicate the default non-covalent interactions between NADH and all atoms within 5Å to it.

- 14) To customize the visualized interactions click on the sidebar icon below the “components”. Click on “Non-covalent Interactions” and choose the interactions you would like to visualize. (Try adding in the “ionic interaction”)

**Q18. Why do you think we can assume that amino acid residues that are up to 5 Å away from NADH are involved in binding the coenzyme to the enzyme?**

**Q19. Insert a screen capture of the pfLDH active site residues interacting with NADH below. Identify the conserved Histidine residue in the active site and label it on your figure. Label as many of the interacting residues as you can on your figure.**

- 15) Repeat steps 9-15 for hLDH-B.

**Q20. Compare the active site residues you identified through molecular visualization to the residues you identified during the analysis of the primary structure alignment.**

## **CONNECTING STRUCTURE TO FUNCTION:**

### **Learning Objectives for this section**

- Explore the molecular details of the binding of a competitive inhibitor to the LDH active site.
- Compare and contrast the molecular details of the inhibitor binding to hLDH and pfLDH and discuss the meaning of those differences in terms of drug design for treating malaria.

After her molecular explorations of the LDH active site, Maria starts to understand how small structural differences especially around the active sites of enzymes can greatly impact enzyme function. She remembers from her biochemistry class in college that competitive inhibitors bind at the active site of an enzyme and compete for binding with the enzyme's natural substrate. Hence, she reasons that it should be possible to find a competitive inhibitor which effectively inhibits pfLDH, but not hLDHB if the alteration of the kinetic parameters for the respective enzymes (pfLDH and hLDH-B) are sufficiently different due to differential binding of the inhibitor to the two active sites. While she is reviewing her understanding of how a **competitive inhibitor** works to reduce the *activity* of an enzyme, Michelangelo calls her to let her know that he has come across an azole based compound, 4-HYDROXY-1,2,5-OXADIAZOLE-3-CARBOXYLIC ACID (known as OXD1 or OXQ) as a possible competitive inhibitor of pfLDH against its substrate lactate in a published journal article (The Journal of Biological Chemistry, 2004, 279(30), 31429-31439).

During drug design, scientists examine proteins in painstaking detail to take advantage of small structural details in designing specific and potent drugs. The first step in this process is most often analyzing structures of protein targets in order to facilitate the design of molecular libraries that could have leads in specificity or potency. *Specificity* relates to how well a certain drug would interact with a protein of interest compared to any other similar protein, while *potency* is used to describe how effective the drug is at producing a desired effect.

Small structural differences especially around the active sites of enzymes can be used to guide inhibitor-based drugs. In the case of malaria, the authors of this paper synthesized a series of compounds they hoped to potently inhibit pfLDH without severe toxicity in humans due to differences in the site that determines substrate specificity. They identified the compound QXD1 via an enzyme assay-based high throughput screen and showed that it inhibited pfLDH with over 100 fold lower IC<sub>50</sub> compared with hLDH. This meant that the concentration of OXD1 required for 50% inhibition of the LDH in a solution for human LDH is much greater than for parasitic LDH. Hence, QXD1 could selectively reduce the activity of pfLDH without a significant reduction in the human LDH activity.

Excited with the prospect of OXD1 as a suitable antimalarial drug, Maria and Michelangelo sat down to compare the crystal structures of the enzyme-inhibitor complexes solved by these researchers: 1T24 (pfLDH complexed with OXD1 and NAD<sup>+</sup>) and 1T2F (hLDHB complexed with OXD1 and NAD<sup>+</sup>)

## Analyzing the 3D structure of hLDH-B and OXQ binding

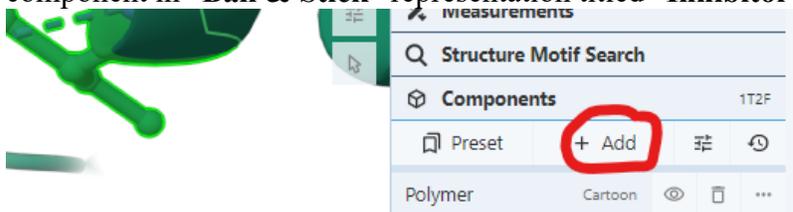
- 1) Go to the RCSB Protein Data Bank (<https://www.rcsb.org/>) and search **1T2F**.
- 2) Go to the “Sequence” tab on the top which displays a graphical representation of several sequence derived information about this structure.

**Q21. Based on the information presented, list the residue numbers for residues that bind to OXQ.**

- 3) Now go to the “3D View” tab to display the 1T2F structure.
- 4) Set the representation to “**Cartoon Representation**” if it isn’t already and hide the water molecules.
- 5) In the sequence bar, change the selection to **OXQ** (3: 4-Hydroxy-1, 2, 5-Oxadiazole-3-Carboxylic Acid) to focus on the ligand.
- 6) Select and make this inhibitor a component labeled “**OXQ**” using “ball & stick” representation.
- 7) Close the selection mode using the **x** symbol at the right of the toolbar, then click on that “**OXQ**” component to focus in on the inhibitor.
- 8) Hover over the OXQ structure (check its identity in the bottom right corner) and click on it to make it the focus. The surrounding interactions will be visible.

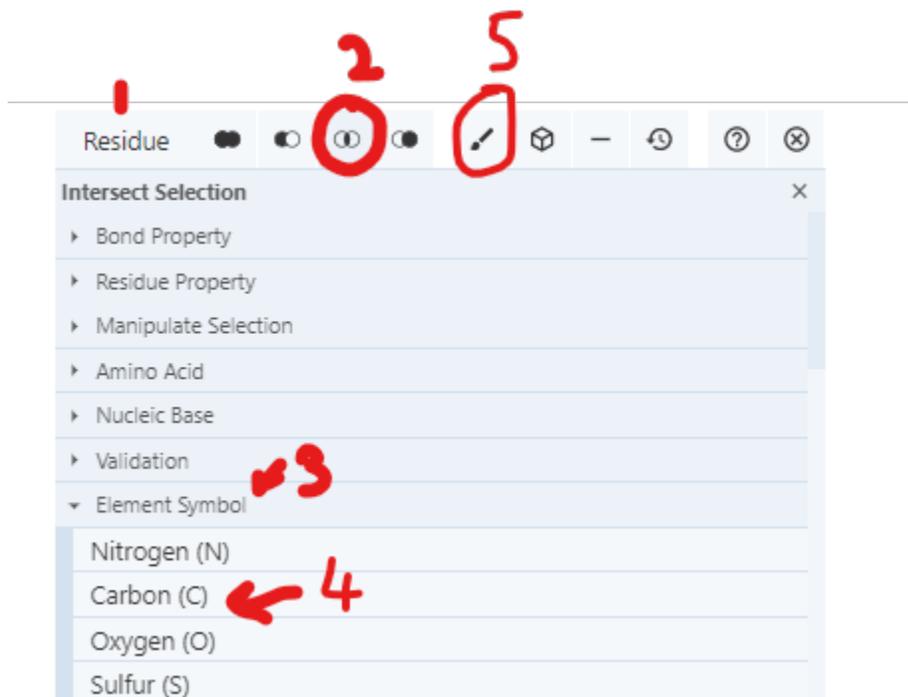
**Q22. What other small molecule is in this zoomed view? What does this imply in terms of the binding site for the inhibitor with respect to the functional enzyme?**

- 9) Under “**Components**” there should be a tab titled “**Focus: Surrounding 5A.**” This represents the nearby residues and interactions within a 5 angstrom distance from the selection. Click on the **3 dots** symbol to the right of this component and choose “**Select This**” on the dropdown menu to highlight all these surrounding residues.
- 10) Under the “Components section click on the “**+Add**” tab and make this selection a new component in “**Ball & Stick**” representation titled “**Inhibitor Binding Residues.**”



- 11) Now you have 2 components, one for the OXQ inhibitor and another for its surrounding residues.
- 12) Clean up the visualization by hiding the rest of the structures using the **eye** symbol next to “**Polymer**” and “**Ligand.**” If you have anything selected you can hide the “[Focus] Target and Surroundings” components or click away to deselect.
- 13) To show the related interactions, under the residues component, add the representation called “**Non-covalent Interactions.**”

- 14) Make the inhibitor stand out by clicking on the **3 dots** next to the OXQ component in the sidebar and finding the subheading “**Ball & Stick Representation.**” Click on this to open a dropdown menu and change the “Color Theme” to “**Element Symbol.**”
- 15) An additional option called “Carbon Color” shows on the dropdown menu, click on the **3 dots** to the right and set it to “**Element Symbol**” (default may say “Chain Id”). Set “Saturation” to the maximum (6). The carbons of OXQ should now be a different color than the LDH. This will allow us to easily find the atoms that participate in hydrogen bonding and additional noncovalent interactions.
- If you don’t see a color change on the OXQ (green to pink), you may need to hide a different component, such as the residues.
  - You can independently “paint” any element with any color of your choosing to help with visualization (remember the default colors for nitrogen (blue) and oxygen (red) are already chosen in this view. Ex. Select NAD+ by clicking on it after activating the “select tool (arrow). In the selection tool bar make sure the “residue” option is visible. Then click on the “intersection” symbol and click on element symbol which will bring up another scroll down menu (you may actually scroll down with the side slider to see it). Click on carbon. Then go to the brush symbol which opens up a color palette. Here you can choose any default color or type in the RGB color number designations to make your own colors. You have the option of applying this color to “all” representations of your selection (in this example carbons of NAD+) or click on “All” box to open up a dropdown menu to choose which representation you want the coloring to apply to. For this example choose “Ball and Stick” and the color gray. Then click “**Apply**”
  - If you like you can repeat the same procedure to color the carbons of all the residues from LDH “cyan”



16) Adjust your view and reposition the structure by rotating it to find a good angle to see the OXQ inhibitor and most of the interacting residues. You can either label everything in Mol\* and then take a screenshot or take the screenshot and then label it on your document.

- To label the residues in Mol\*, use the “**Measurement**” tool in the sidebar. You can only add one label at a time, so the **Label** tool will only apply to your most recent selection (appears with the number 1). This adds the corresponding three-letter code and number to each residue. You can adjust the font size but not the location

(Click residue) → Measurement → Add → Label (1st selection item)

**Q23. Insert a screenshot of your view below and label the residues you see (two will be small ligands and the rest amino acid side chains from LDH) if you have not already done so in Mol\*.**

Now let’s show some interactions between different components in this view.

17) To ensure that you are seeing ALL the different type of interactions (and not just the defaults), go to the sliding bar icon under components and click. In the dropdown menu that opens click on “non-covalent interactions” and then turn all interactions on (except for weak H-bonds)

18) Select NAD<sup>+</sup> and OXQ by clicking on both residues while the selection tool is engaged and set to “residue” (you should see them highlighted).

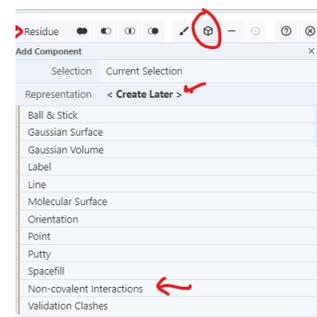
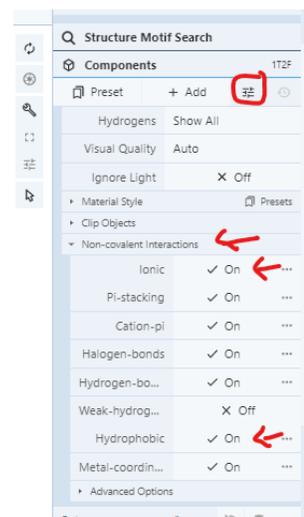
19) Click on the “cube” icon to create a new component.

20) Click on the “Representation” box and scroll down (almost to the end) to select “non-covalent” interactions. Create the component.

**Q24. What are the three different types of interactions that are displayed? (You can hover over the dashed lines and read the identity of each interaction on the bottom right corner of the canvas). Which atoms do these interactions involve? Describe each interaction in your own words. Can you think of any other biochemistry contexts you might have encountered each of these interactions? List some examples you remember.**

21) Now select the “Inhibitor Binding Residues” and OXQ and create a new component that shows the interactions between them.

**Q25. Based on the interactions revealed, list the residues that bind with OXQ and the type of interaction they are involved in. Do they match the ones you retrieved from the PDB site in Q21?**



**Q26. What is the major non-covalent interaction that ensures the strong binding of OXQ to LDH?**

Finally, let's measure some distances between the inhibitor and the conserved H193 in the active site.

- 22) Hide all the interactions to have a cleaner view.
- 23) To measure bond distances, use the selection tool and change the type in the top toolbar from "Residue" to "Atom/Coarse Element."
- 24) Click on NE2 on H193 (the nitrogen on the ring closest to OXQ) and then on O7 on OXQ (the oxygen closest to H193)
- 25) Click on "Measurement" in the sidebar, click "Add," then "Distance" which adds the bond distance on the selected bond.
- 26) Now add in all the other H-bonds distances between OXQ and the surrounding residues.

**Q27. Insert a figure below showing all the H-bond distances between OXQ and the interacting residues in the hLDH-B active site. Also take a screenshot of all the distance measurements from the sidebar and add below.**

***Analyzing the 3D structure of pFLDHB and OXQ binding:***

*Repeat the same sequence of instructions you completed for analyzing the interaction between OXQ and human LDH in steps 1-26 in the following section using the PDB ID: 1T24*

**Q28. Insert a figure below showing all the H-bond distances between OXQ and the interacting residues in the hLDH-B active site. Also take a screenshot of all the distance measurements from the sidebar and below.**

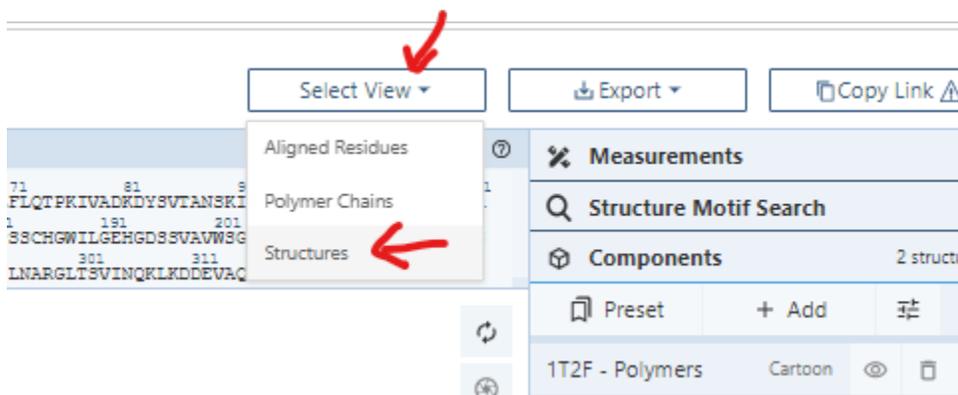
After exploring the inhibitor binding to both LDH active sites separately, Maria is not sure if there are enough structural differences between the two enzymes in the active site to account for the reported 100 fold activity difference. So she decides wants to do a structural alignment to get a better understanding.

***Structural Alignment of pFLDH and hLDH-B active sites with the inhibitor OXQ:***

- 1) Go to <https://www.rcsb.org/> and click on the "Analyze" tab on the top bar and select "Pairwise Structure Alignment"



- 2) Enter **1T2F** and chain **A** in the first row of “**compare structures**” and **1T24** and chain **A** in the second row. Keep the default parameters (for rigid body alignment). Click “**compare**” This will return a screen that has the two structures superimposed on their entire first subunit.
- 3) Click on the wrench icon to expand the view to include full Mol\* capabilities.
- 4) Under “select View” click “structures” which will bring in the rest of the structures to the view.



- 5) Select the OXQ from the 1T2F structure and create a component. Repeat for 1T24 structure. Make sure that you color them distinctly so that you can easily identify them.
- 6) At this point you will need to do some clean up to get rid of components you are not interested in as the view can get very crowded quickly.
- 7) In the selection menu change the first option to “chain” and click on the extra chains (the ones that are not aligned) to select. Then use the “-“ on the selection tool bar to remove them.



- 8) Once you remove the elements you do not want to see, click on the inhibitor component to bring it into focus and create a component with all the residues surrounding it as you did earlier. Repeat for the inhibitor in the second structure. Now you can hide everything else and just visualize the inhibitors and the residues they interact with in the aligned structures to identify major changes.

**Q29. Insert a screenshot of the superposition of the inhibitor in the pfLDH structure with its interacting residues in the active site and the hLDH structure below and highlight some of the major differences.**

**Q30. Based on the structural changes you observed and the distances you measured for the different interactions between the inhibitor and the enzyme for pfLDH and hLDHB, do you expect the compound to bind more tightly to pfLDH or hLDH? Justify your choice by providing specific molecular support.**

***Structural changes explains functional differences:***

1. Go to Binding DB to obtain the  $K_I$  for OXQ  
<https://www.bindingdb.org/rwd/bind/index.jsp#>
2. Enter in the search bar: 4-HYDROXY-1,2,5-OXADIAZOLE-3-CARBOXYLIC ACID.  
Select the first compound.

**Q31. Based on the information in the “Affinity Data” columns, what is the  $K_I$  for this compound for pfLDH and hLDHB?**

**Q32. Would you expect the  $K_I$  to be higher or lower for human LDH if OXQ had lower binding affinity in human LDH?**

**Q33. Based on your analysis of the OXQ inhibitor, would you recommend that Maria uses OXQ as an antimalarial drug? Why or why not? Be sure to include discussion of active sites and binding affinity in your answer.**

## ASSESSMENT OF STUDENT LEARNING:

### *Learning Objectives for this section:*

- Evaluate the success of an alternative drug treatment
- Identify the components necessary for a viable drug inhibitor

Though these recent discoveries in antimalarial activity with the OXQ inhibitor have been promising, a mode of distributing it in an accessible drug form to the public has yet to be found, and could take years to finalize. In the meantime, Maria must opt for a treatment that is already established. Fortunately for Maria, there has been major progress in malaria treatment, specifically with chloroquine! Chloroquine is an approved drug that effectively targets *Plasmodium falciparum* LDH.

View the following sources to familiarize yourself the scope of chloroquine as an accessible malaria treatment:

<https://www.cdc.gov/malaria/resources/pdf/fsp/drugs/Chloroquine.pdf>

Here is the paper describing one of the studies of chloroquine inhibition of *pf*LDH (<https://www.jbc.org/content/274/15/10213.full.pdf>). Read the *Experimental Procedures* Section.

**Q1. What were the reported  $K_I$  values of chloroquine to pig LDH and *pf*LDH?**

**Q2. Why did the researchers use pig LDH instead of human LDH? Justify their decision by performing a sequence alignment on pig LDH and human LDH using UniProt. Include a screenshot of your alignment below.**

**Search the PDB for a structure of *Plasmodium falciparum* in a complex with chloroquine and visualize the structure with Mol\*.**

**Q3. What is the PDB ID for your selected structure?**

**Q4. By following directions in the previous sections, create a figure of chloroquine interacting with specific LDH residues. Label the important residues and ligands, and non-covalent interactions, and insert your screenshot below:**

**Q5. Where on the molecule does chloroquine bind? What kind of inhibition does chloroquine pose on the *Plasmodium falciparum* LDH?**

**Q6. Using the study on chloroquine on pig LDH and *pf*LDH, as well as the structural**

**characteristics you observed using Mol\*, how is chloroquine an effective antimalarial agent?**

**Q7. Based on what you have learned about OXQ and chloroquine inhibition, what are the key characteristics of a viable drug inhibitor?**