Metabolism in erythrocytes

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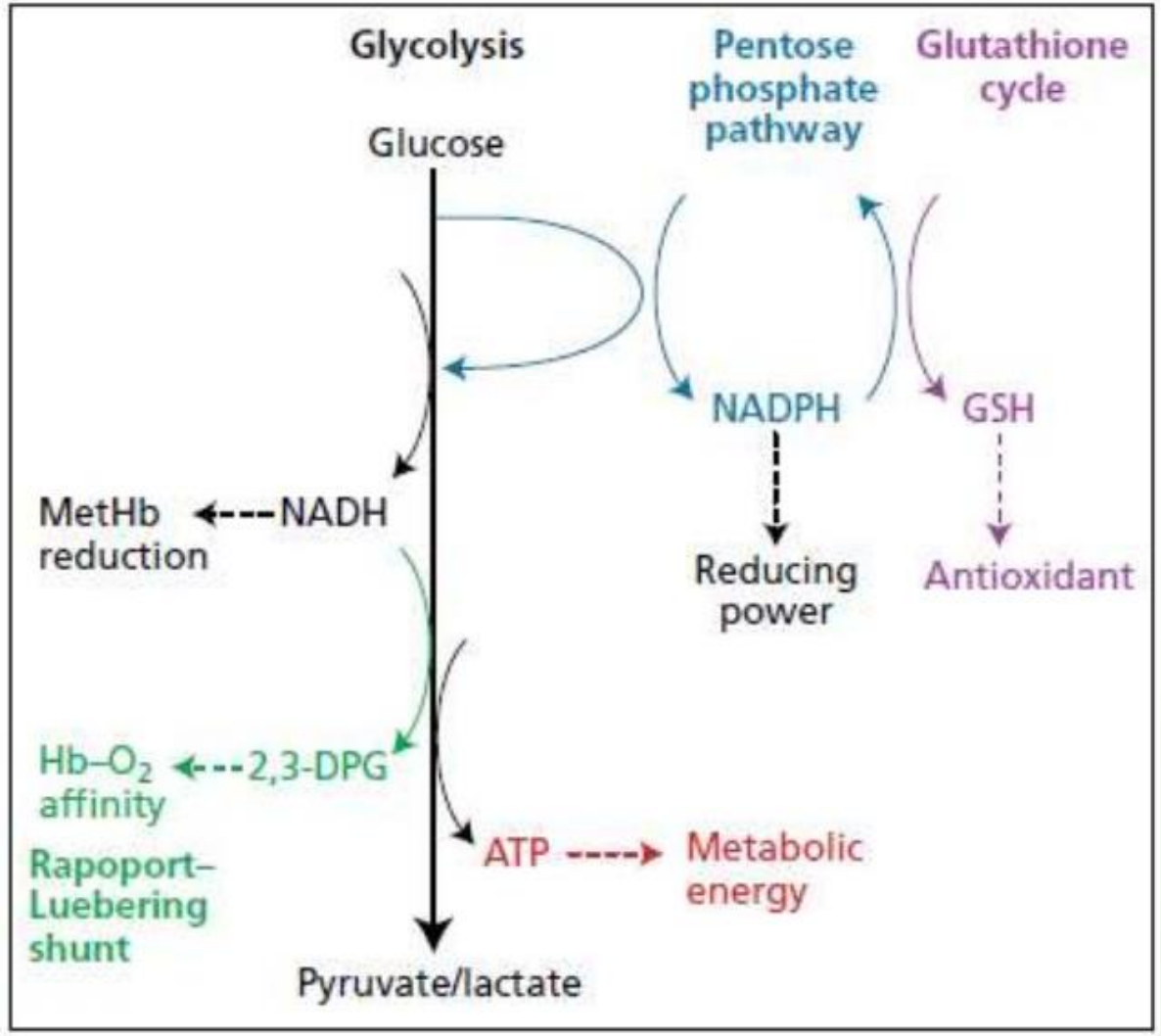
Hematopoietic-lymphatic system

- This lecture
- Lippincott's Biochemistry, 7th edition
- The Medical Biochemistry Page (https://themedicalbiochemistrypage.org/)

Carbohydrate metabolism in RBC

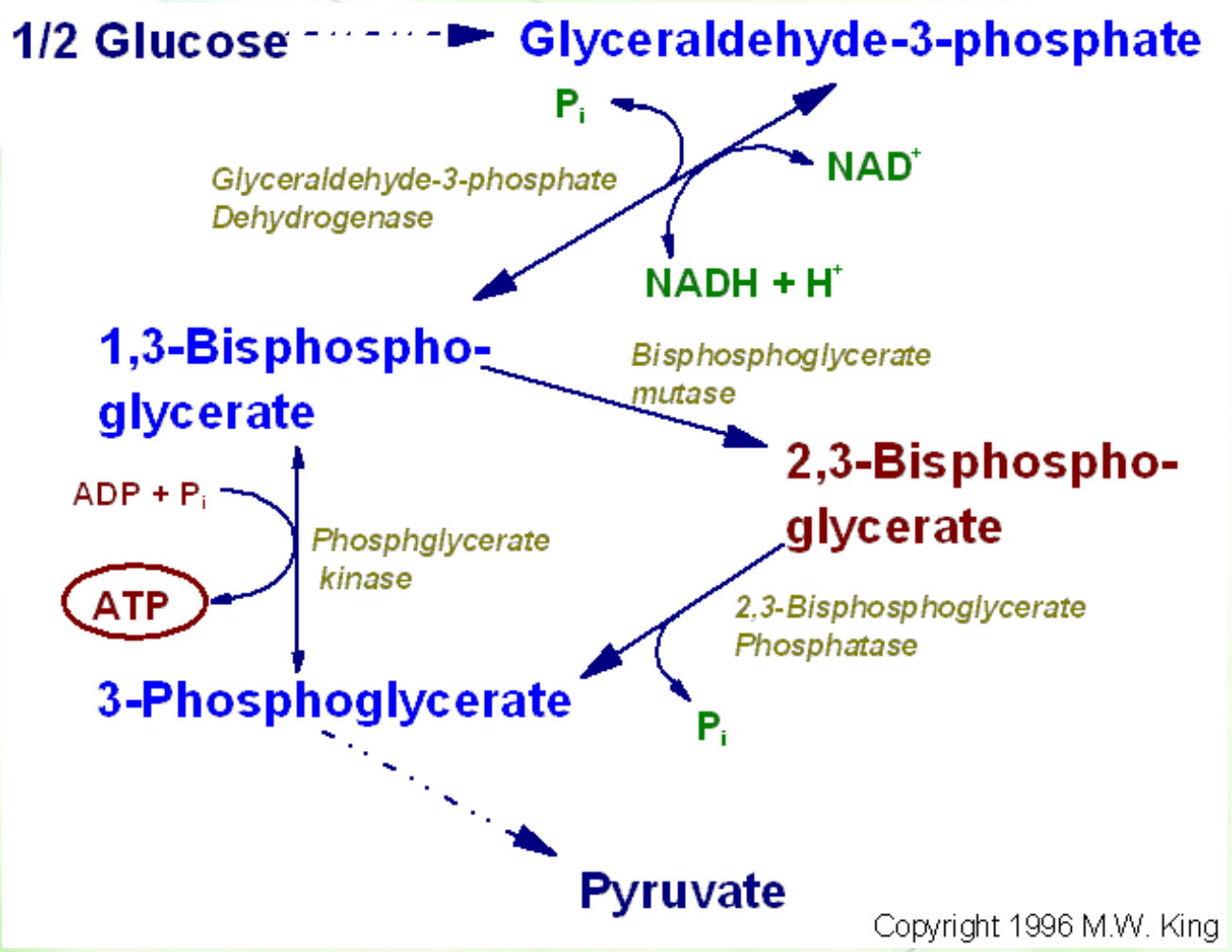
- Glycolysis
  - 2,3-bisphosphoglycerate (2,3-BPG)
  - NADH
- Pentose phosphate pathway
  - NADPH



2,3-bisphosphoglycerate (2,3-BPG)

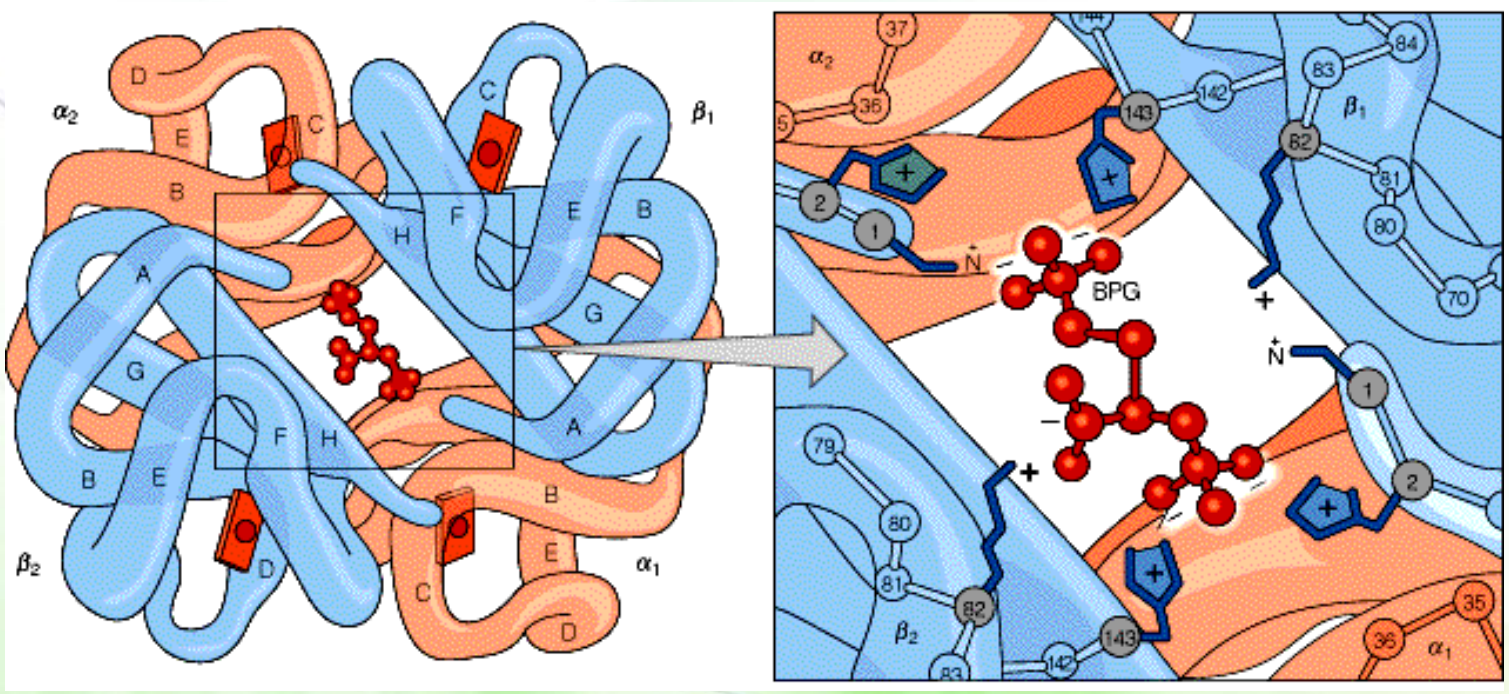
Generation of 2,3-BPG

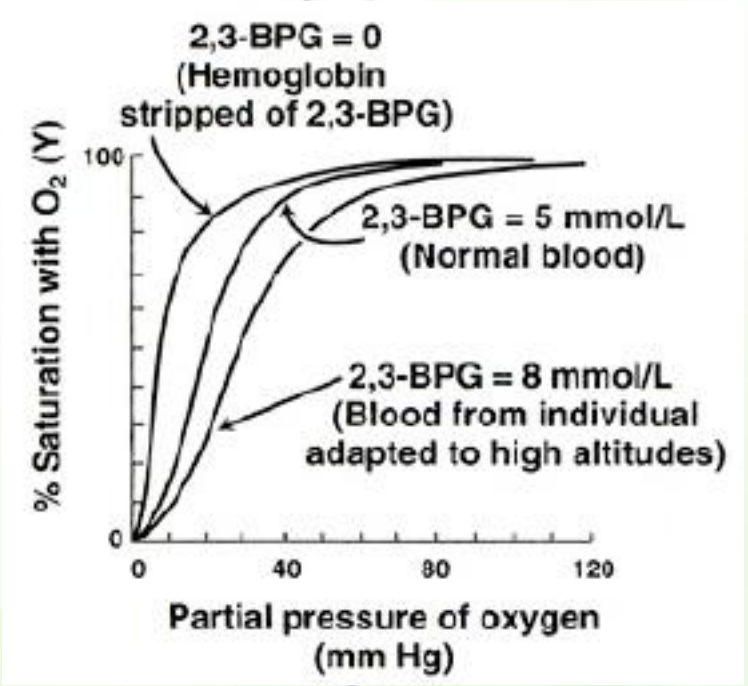
- 2,3-bisphosphoglycerate (2,3-BPG) is derived from the glycolytic intermediate 1,3-bisphosphoglycerate.
- It can re-enter the glycolytic pathway.
  - The erythrocyte loses the ability to gain 2 moles of ATP.



Effect of 2,3-BPG on Hb

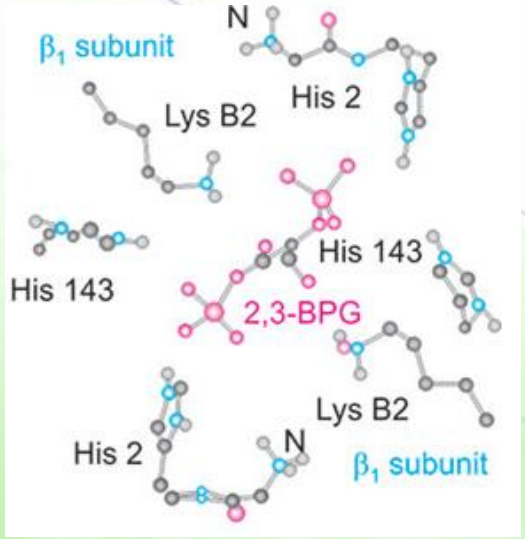
- 2,3-BPG occupies the center of deoxygenated Hb stabilizing it in the T structure.
- When 2,3-BPG is not available (not bound), Hb can be easily converted to the R-structure.

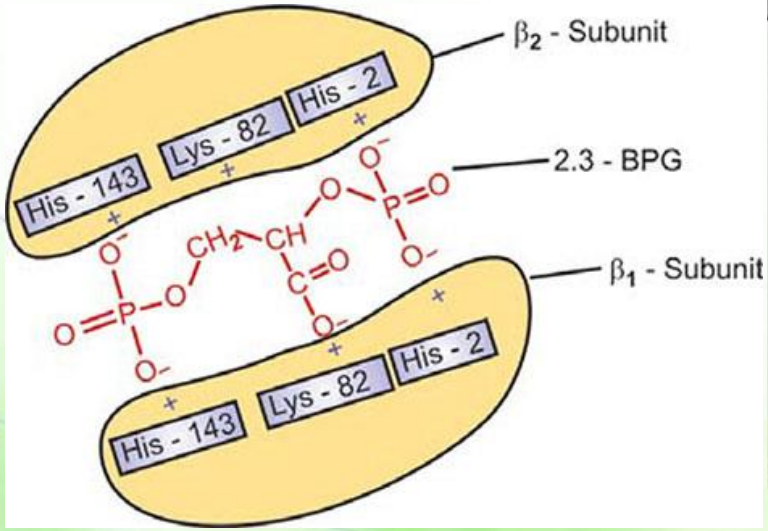




2,3-BPG and HbF

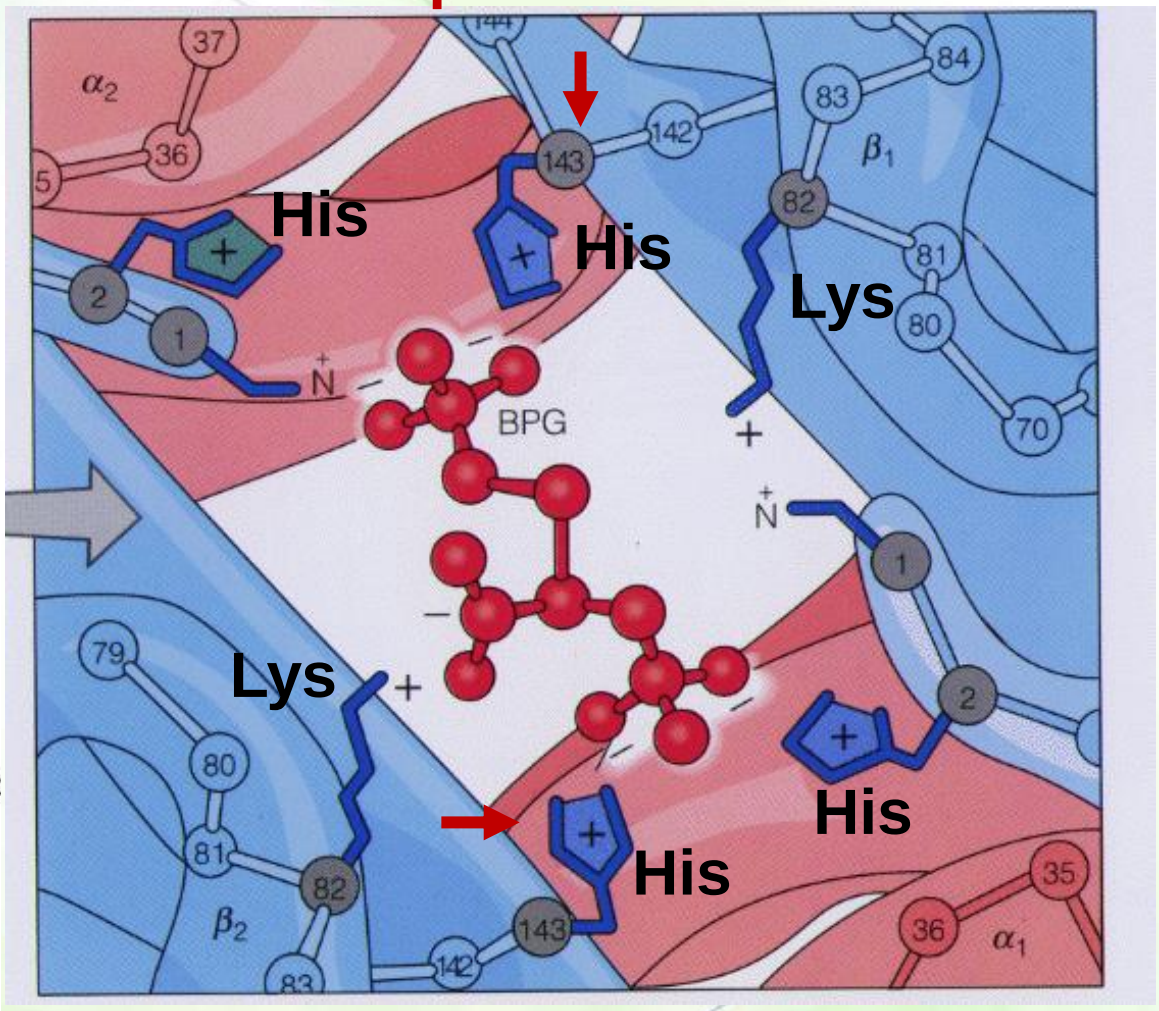
- BPG interacts with several groups including a lysine, His143, His2, and N-terminal ends of the β chain.
- Fetal hemoglobin (HbF) binds 2,3-BPG much less strongly than HbA.





His143 is replaced by a serine in the γ chain.

Re-record

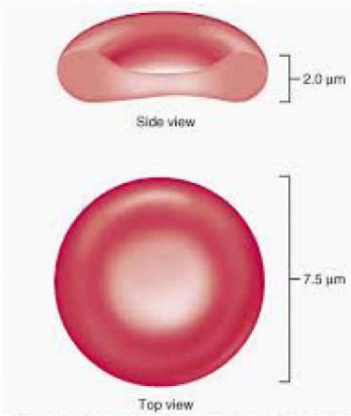


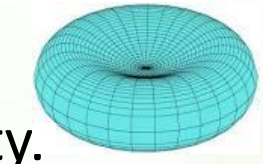
Glycolysis

Main purpose

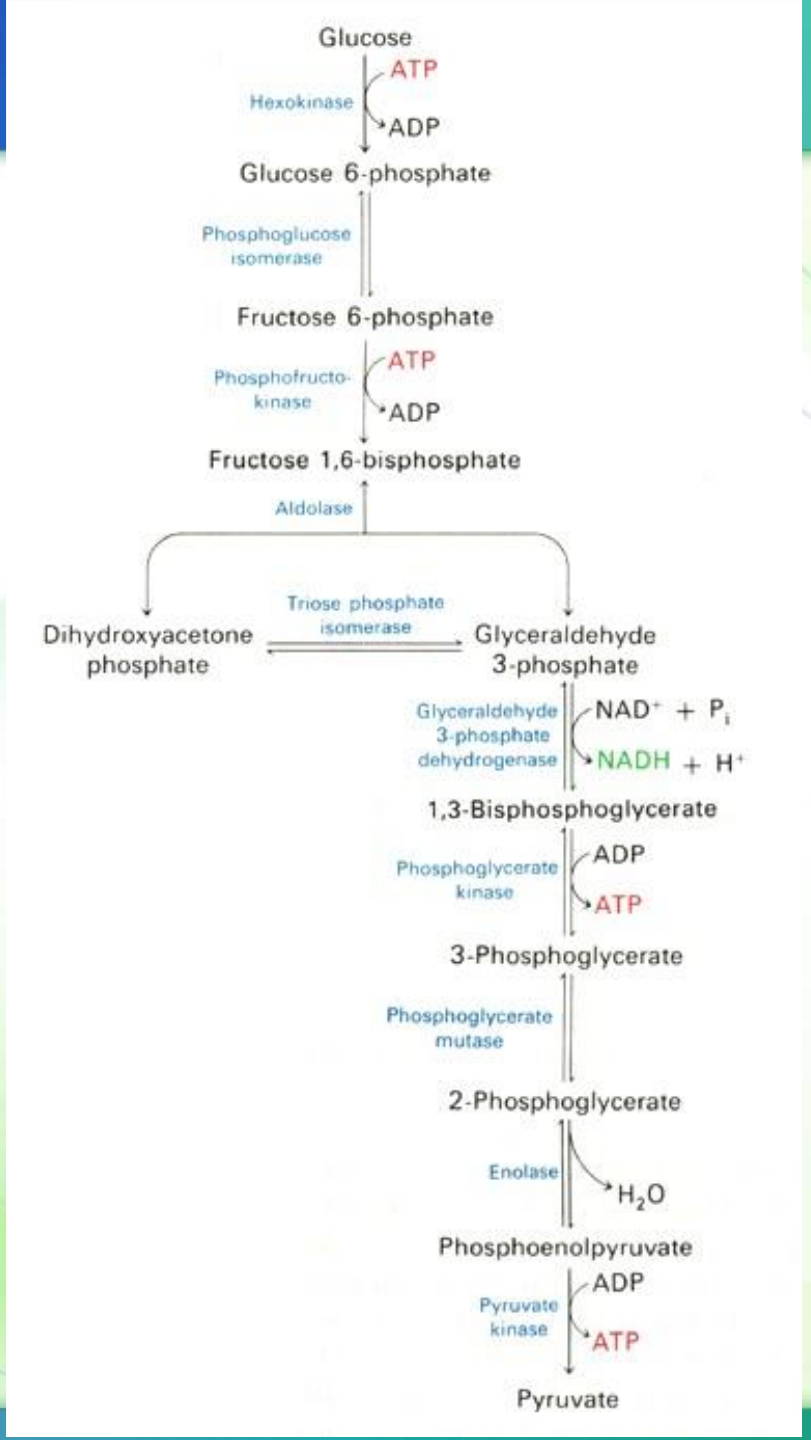
Re-record

- Glycolysis provides
  - NADH for **reduction** of methemoglobin (hemoglobin with oxidized Fe3+ in heme)
  - ATP for
    - Modifying sugars and proteins
    - Maintaining membrane asymmetry
    - Functions of membrane ion pumps
    - Regulating cytoskeletal proteins
      - Maintenance of the discocyte shape, optimal viability and functional capacity.



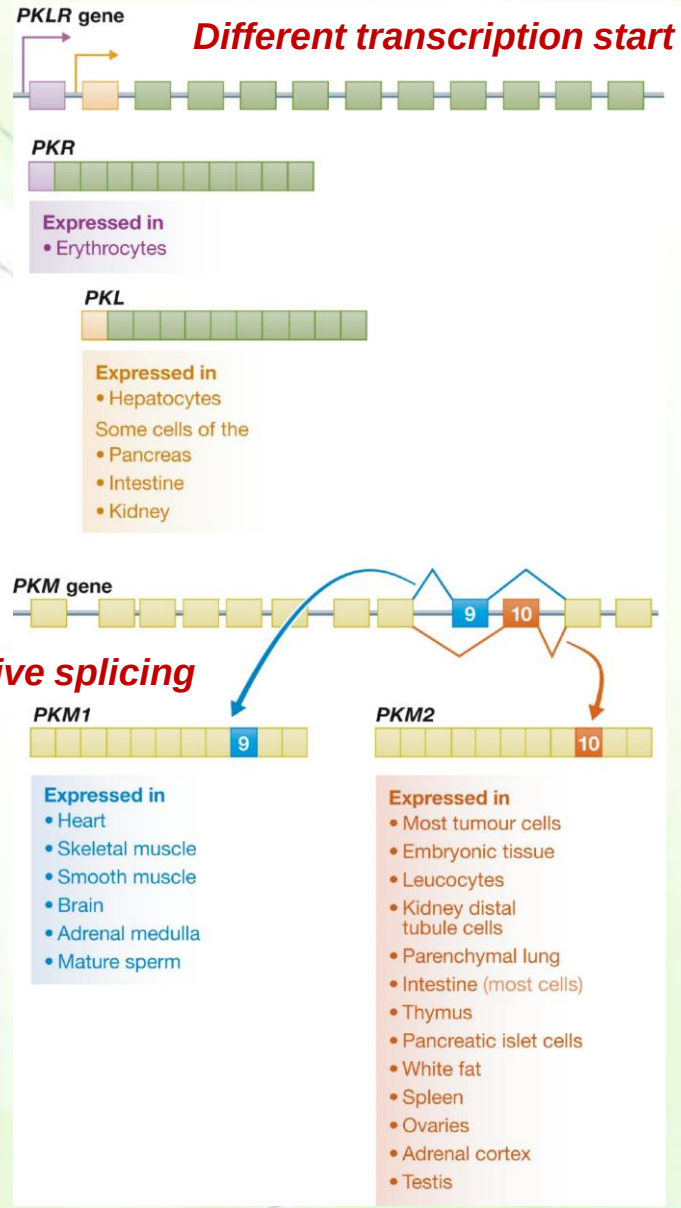


which is critical for the


Glucose
ATP
Hexokinase
ADP
Glucose 6-phosphate
Phosphoglucose isomerase
Fructose 6-phosphate
ATP
Phosphofructo-kinase
ADP
Fructose 1,6-bisphosphate
Aldolase
Dihydroxyacetone phosphate
Triose phosphate isomerase
Glyceraldehyde 3-phosphate
Glyceraldehyde 3-phosphate dehydrogenase
NAD+ + Pi
NADH + H+
1,3-Bisphosphoglycerate
Phosphoglycerate kinase
ADP
ATP
3-Phosphoglycerate
Phosphoglycerate mutase
2-Phosphoglycerate
Enolase
H2O
Phosphoenolpyruvate
Pyruvate kinase
ADP
ATP
Pyruvate

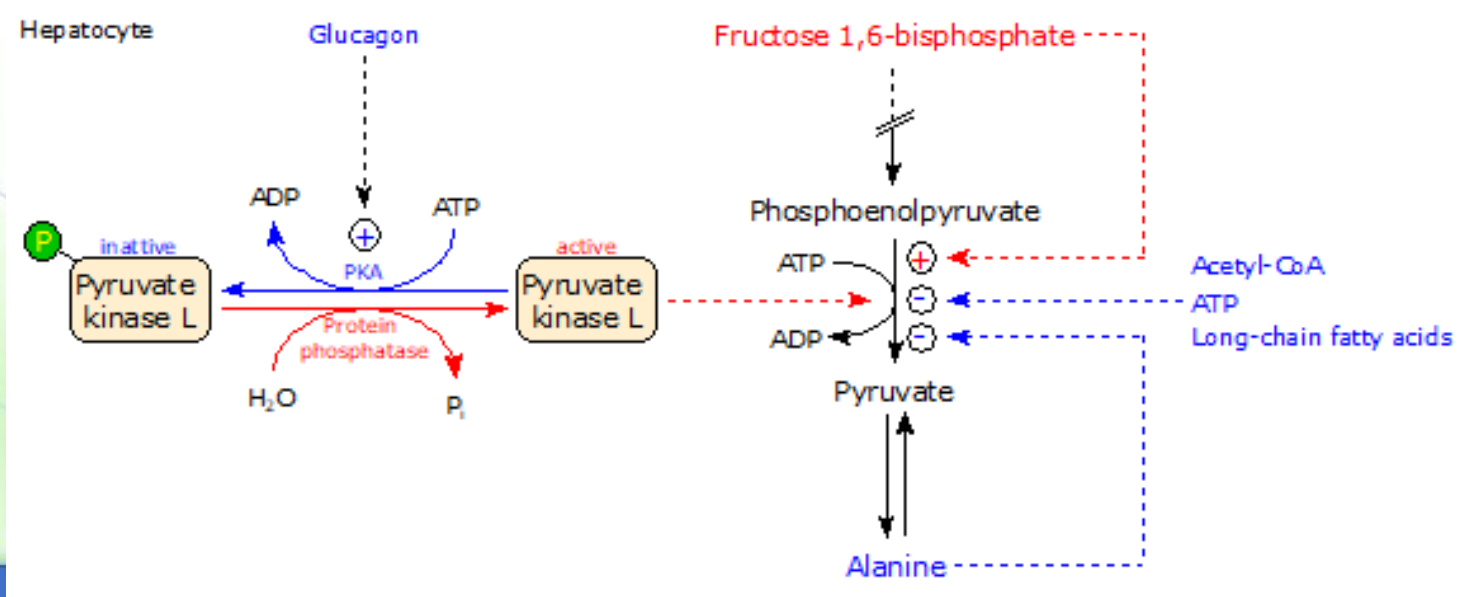
Pyruvate kinase isozymes and regulation

- There are two isoenzyme genes of PK and each produces two isoforms:
  - PK**L** (liver) and PK**R** (erythrocytes) are produced from PKLR gene.
  - PKM1 (muscle and brain) and PKM2 (fetal and most tissues) produced from PKM gene.
- Fetal PK isozyme (*PKM2*) has much greater activity than the adult isozymes.
  - Fetal erythrocytes have lower concentrations of glycolytic intermediates including 1,3BPG (and 2,3BPG).
    - *Remember: lower 2,3BPG means higher Hb in R-state.*



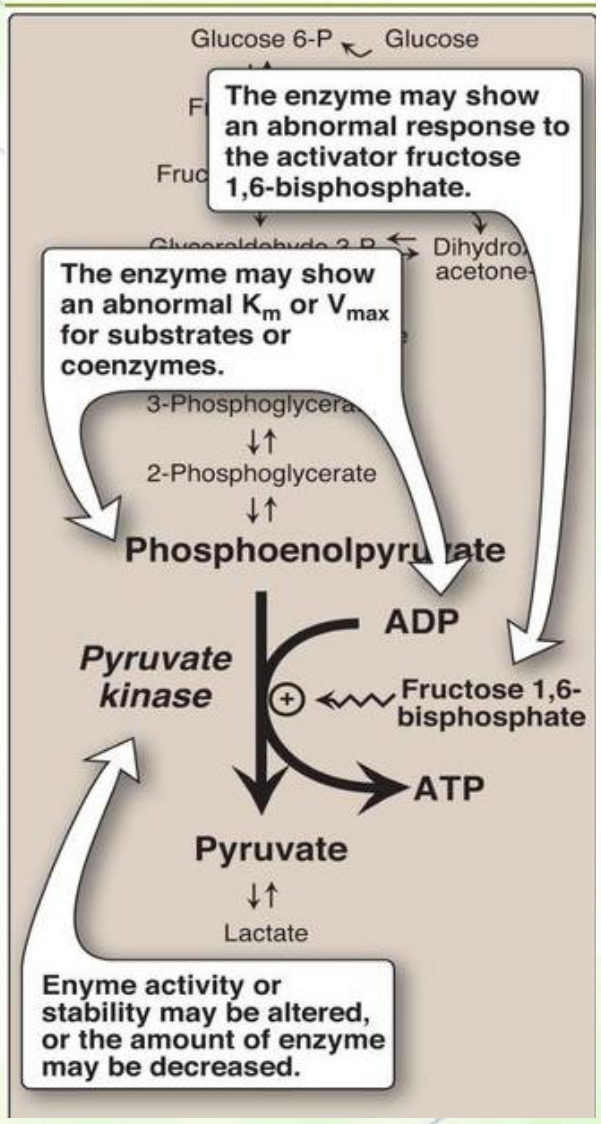
Regulation of PK

- The PKLR is allosterically regulated:
  - inhibited by ATP, acetyl-CoA, alanine, and long-chain fatty acids and by phosphorylation by protein kinase A.
  - activated by F1,6-BP.
- The liver enzyme (PKL) is also controlled at the level of synthesis.
  - Increased carbohydrate ingestion induces the synthesis of PK.



PK deficiency

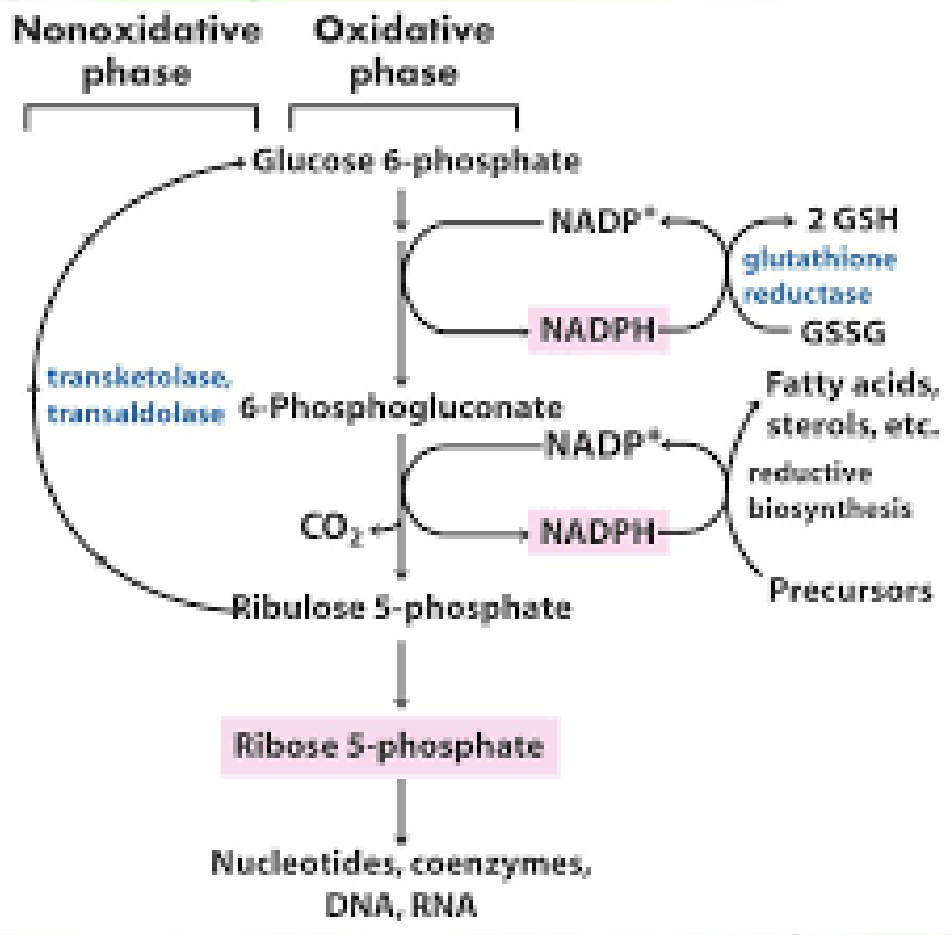
- Genetic diseases of adult erythrocyte PK where the kinase is virtually inactive.
- The erythrocytes have a greatly reduced capacity to make ATP, which causes hereditary hemolytic anemia.
- The severity of the disease depends on the degree of enzyme deficiency (5-35%) and ability to produce 2,3-BPG.
- Liver is not affected since expression is stimulated.



The pentose phosphate pathway

Two phases of pentose phosphate pathway

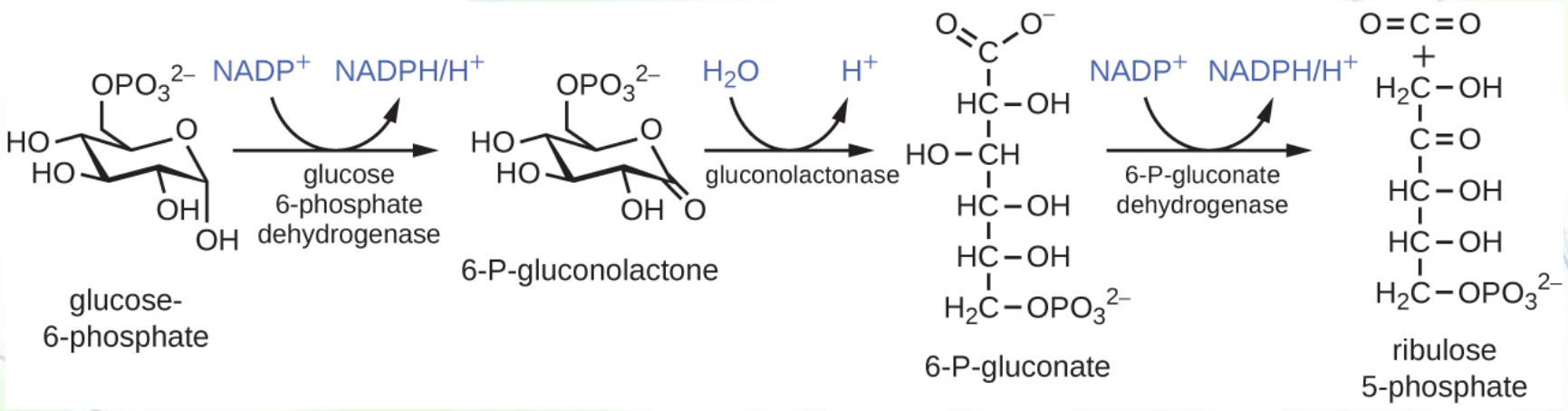
- The oxidative generation of NADPH
  - NADPH is generated when glucose 6-phosphate is oxidized to ribulosese 5-phosphate.
- The nonoxidative interconversion of sugars



$$\text{Glucose 6-phosphate} + 2\,\text{NADP}^+ + \text{H}_2\text{O} \longrightarrow \text{ribose 5-phosphate} + 2\,\text{NADPH} + 2\,\text{H}^+ + \text{CO}_2$$

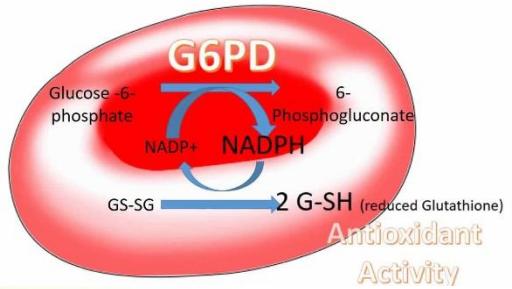
The first step

- The oxidative phase of the pentose phosphate pathway starts with the dehydrogenation of glucose 6-phosphate by glucose 6-phosphate dehydrogenase.



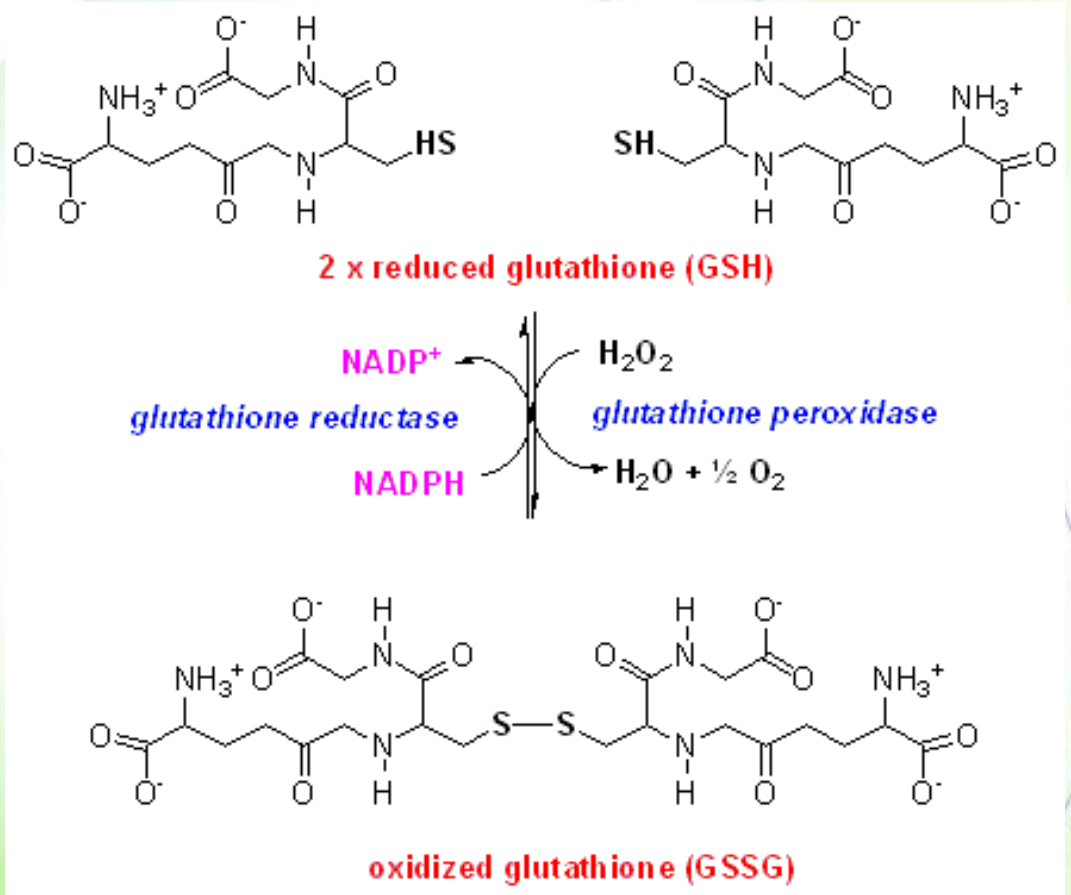
- G6PD is highly specific for NADP+, relative to NAD+
- The reaction is irreversible, is the rate limiting reaction.
- High levels of NADP+ stimulate the reaction .

Oxidative stress and glutathione



- Oxidative stress within cells is controlled primarily by the action of glutathione (GSH).
- GSH reduces peroxides via glutathione peroxidase.
- GSH is regenerated via NADPH-dependent glutathione reductase.
- The PPP in erythrocytes is the only pathway to produce NADPH.

  PPP consumes almost 10% of glucose by erythrocytes.



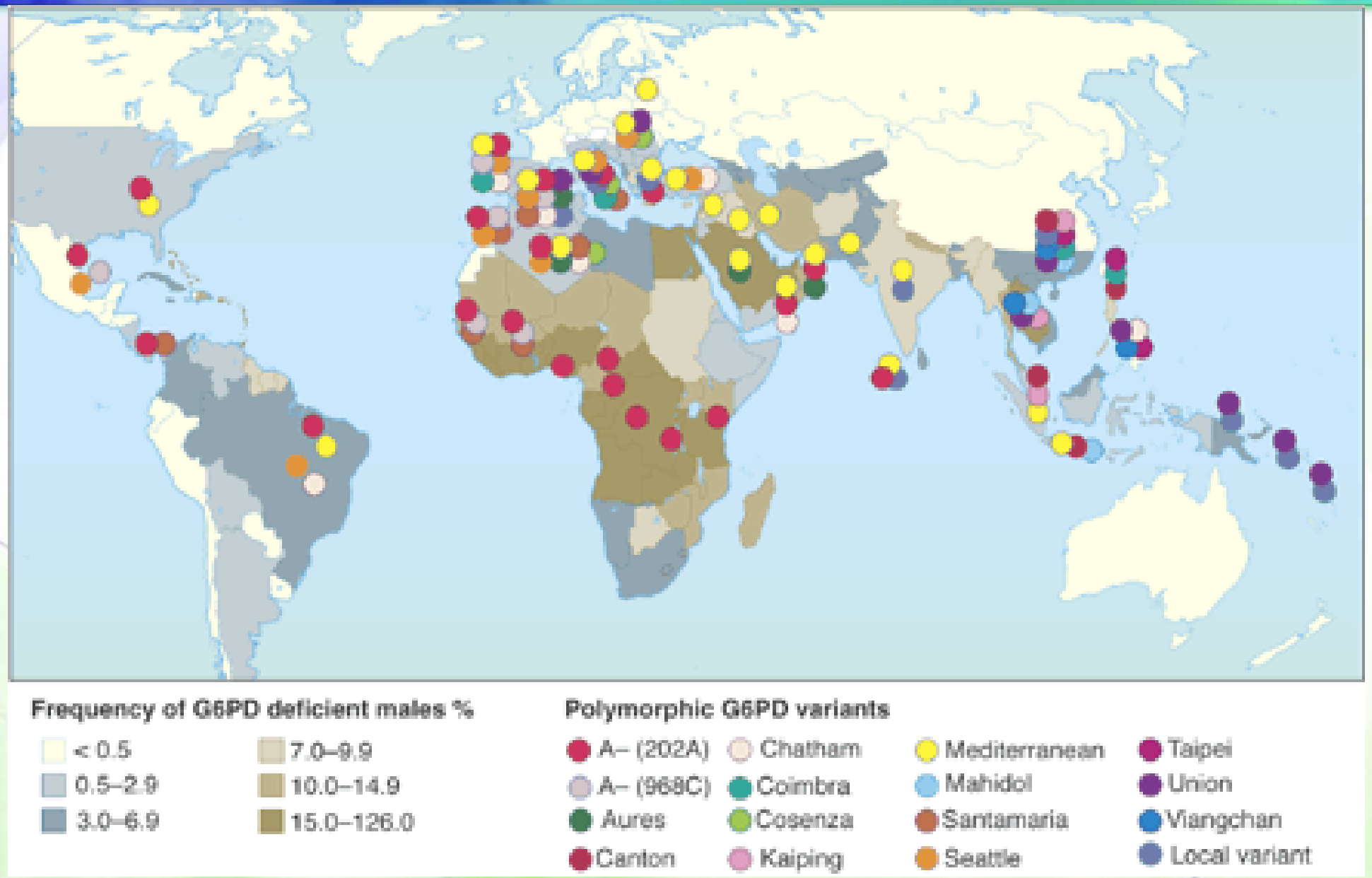
Low GSH levels

- The inability to maintain reduced glutathione in RBCs leads to increased accumulation of peroxides, predominantly H2O2, resulting in
  - Weakening of the cell membrane and concomitant hemolysis
  - increasing rates of oxidation of hemoglobin to methemoglobin and other proteins including membrane proteins, insolubilizing them forming Heinz bodies, weakening the cell membrane.

Glucose-6-phosphate dehydrogenase deficiency

G6PD deficiency

- Glucose-6-phosphate dehydrogenase (G6PD) deficiency is a group of heterogeneous disease with significantly reduced activity.
  - Hemolytic anemia
    - particularly after the administration of drugs, during infections and in the neonatal period (jaundice)
- Deficiency of G6PD is most prevalent in individuals of African, Mediterranean, and Oriental ethnic origins.
- It is the most common enzyme deficiency worldwide.
- G6PD gene is located on the X chromosome.
  - Inheritance of G6PD deficiency is sex-linked.


Frequency of G6PD deficient males %
< 0.5
0.5–2.9
3.0–6.9
7.0–9.9
10.0–14.9
15.0–126.0
Polymorphic G6PD variants
A– (202A)
A– (968C)
Aures
Canton
Chatham
Coimbra
Cosenza
Kaiping
Mediterranean
Mahidol
Santamaria
Seattle
Taipei
Union
Viangchan
Local variant

G6PD mutations

- Several hundred G6PD genetic variants have been identified, but most have no clinical symptom.
- Almost all G6PD deficiency variants are caused by point mutations in the gene.
  - Mainly these mutations alter the kinetic properties, stability, or binding affinity to NADP+ or G6P.
- No large deletions or frameshift mutations. Why?

The four classes of G6PD deficiency

Class	Clinical symptoms	Residual enzyme activity
I	Very severe (chronic hemolytic anemia)	<2%
II	Severe (episodic hemolytic anemia)	<10%
III	Moderate	10%-60%
IV	None	>60%

- G6PD B (Normal)
- Abnormal G6PDs
  - Class I are most severe and rare.
  - Class IV: no clinical symptoms
  - G6PD A- (group III or class III)
    - Among persons of African descent
    - It is caused by a single amino acid substitution of Asn to Asp that decreases enzyme stability, but 5-15% of normal activity.
    - The disease is moderate.
  - G6PD Mediterranean (group II or class II)
    - Severe
    - The enzyme has normal stability, but negligible activity.

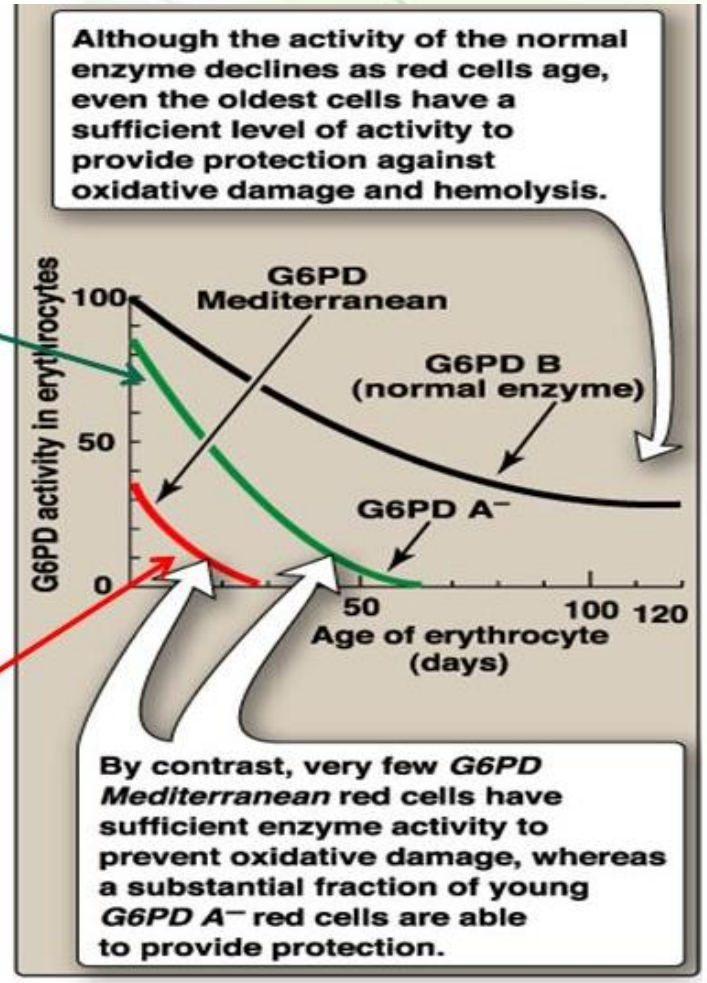
Class II vs. class III

G6PD A- (class III):

Moderate, young RBCs contain enzymatic activity. Unstable enzyme, but kinetically normal

G6PD Mediterranean (II)

Enzyme with normal stability but low activity (severe). Affect all RBCs (both young and old)



Inducers of G6PD deficiency symptoms

- Oxidant drugs
  - Antibiotics, anti-malarial, and anti-pyretics (not acetaminophen)
- Fava beans (favism)
  - Substances capable of destroying red cell GSH have been isolated from fava beans (fool)
  - Favism is most common in persons with G6PD class II variants, but rarely can occur in patients with the G6PD A- variant.
  - Fava beans are presumed to cause oxidative damage by an unknown component
- Infection
  - The most common inducer due to production of free radicals.

Connection to malaria

- Several G6PD deficiencies are associated with resistance to the malarial parasite, Plasmodium falciparum, among individuals of Mediterranean and African descent.
- The basis for this resistance is the weakening of the red cell membrane (the erythrocyte is the host cell for the parasite) such that it cannot sustain the parasitic life cycle long enough for productive growth.