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Introduction

Muscle is a thermodynamic machine that converts chemical energy into work. The production of 30 moles of ATP may be expressed with the following apparent reaction as:

$$C_6H_{12}O_{6\,muscle} + 6O_2 \xrightarrow{30\,ADP + 30\,P \rightarrow 30\,ATP} 6CO_2 + 6H_2O$$

Similarly, ATP utilization for work production may be represented as:

$$ATP_{muscle} \xrightarrow{muscle\ contraction} ADP + P_i$$

Thermodynamic analyses can be used to test the feasibility of processes. The second law of thermodynamics defines entropy and is used to measure energy losses.

- **Entropy** is a measure of the randomness of a system. From the thermodynamic perspective, the diaphragm is an open thermal system and can be regarded as a machine (piston) that converts part of the consumed power in external power during a breathing cycle. **During each breathing cycle, diaphragm operates like a thermal machine (piston) where energy utilized is converted to work by diaphragm muscles.** In this periodically process, the tissue randomness increases due to entropy accumulation, which may lead to a decrease in work efficiency in the diaphragm over time. (In this cycle, the randomness of the tissue increases due to entropy accumulation, which eventually may lead to damage in diaphragm muscle).
- **Exergy** is defined as the maximum useful work, and in every irreversible process, entropy production results in the destruction of the exergy (is an expression that determines the usable energy loss caused by entropy generation)(1-5).
- **Aim of the study is to determine the exergy destruction and entropy generation by using thermodynamic analysis of the work done in the diaphragm muscle.**

Methods

In this study, a human respiratory system was modeled as the diaphragm skeletal muscle. Then, the first and second laws of thermodynamics were utilized to analyze these systems. Mass, energy, exergy and entropy balances are performed around the diaphragm muscles to calculate the glucose consumption, exergy destruction and entropy generation (Fig.1-2).

1. Energy Balance

Energy balance around the muscle system (Fig. 1.), requires:

$$Q - W + \sum_i (mh)_{in} - \sum_i (mh)_{out} = \Delta E = 0$$

where i=1, 2, 3 and 4 refer to glucose, oxygen, carbon dioxide and water, respectively.

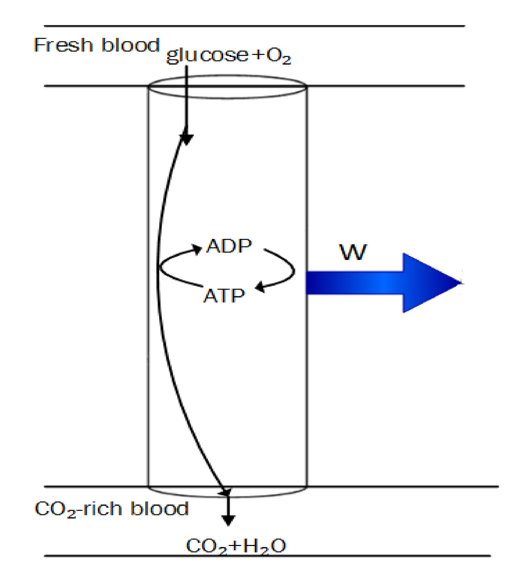

Fig. 1 The schematic description of the muscle contraction process

2. Exergy destroyed in the blood stream

Exergy destroyed in the blood stream is calculated from :

$$Ex_{destroyesd} = Q\left(1 - \frac{T_0}{T}\right) - W + (mex)_{in} - (mex)_{out}$$

3. Entropy Balance

The entropy generation is calculated as:

$$S_{gen} = \frac{Ex_{destroyed}}{T_0}$$

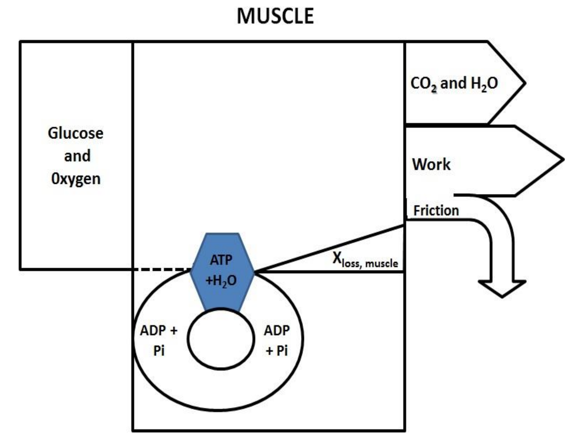

Fig. 2 Schematic diagram of the ATP generation and work performance in the muscle

Results

As a result of the thermodynamic analysis of the work for resting state respiration (diaphragm) performed by a healthy adult individual (Table1);

Table 1. Variation of the glucose consumption rate, exergy destruction rate and the entropy generation rate in the human respiratory (diaphragm) muscles with the second law efficiency (healthy rest subject breathing Work = 3.36 x 10^{-3} kJ/min (min work) - 4.8x10^{-3} kJ/min (max work).

η_{II}	$m_{glucose}$ (mol/min)	$m_{glucose}$ (mmol/min)	Glucose Concentration in Blood (mmol/L)	$Ex_{destroyed,muscle}$ (kJ/min)	$S_{gen,muscle}$ (kJ/K)/min
0.3 (for min work)	2.89x10^{-6}	0.22	4.34x10^{-2}	8.41x10^{-3}	2.82x10^{-5}
0.3 (for max work)	4.13x10^{-6}	0.31	6.20x10^{-2}	1.20x10^{-2}	4.03x10^{-5}

- ✓ **The minimum and maximum values of the exergy destruction** were calculated to change from **8.41x10^{-3} kJ/min** to **12x10^{-3} kJ/min**, respectively.
- ✓ **Entropy generation** was found to be between **2.82x10^{-5} (kJ/K)/min** and **4.03x10^{-5} (kJ/K)/min.**
- ✓ The glucose used by the diaphragm muscle is calculated for minimum and maximum work values.
- ✓ Given the results of the energy balance analysis according to the first law of thermodynamics, **the glucose consumed for this work was calculated as 0.22-0.31 mmol/min.**

Conclusions

When the muscle work done by the diaphragm is maximized, exergy destruction is also increasing. As entropy generation increases with the substrate utilization, entropy generation also increases when the work done by the diaphragm is maximized in the respiration of the healthy individual.

In this thermodynamic analysis, exergy destruction and entropy generation in diaphragm muscles during respiration were in association with the blood circulation, depending on the muscle work.

- ✓ By evaluating the work done by the diaphragm muscle by thermodynamic analysis may provide additional information in determining the work performance related to the respiratory system.
- ✓ In the other words thermodynamic analysis of the diaphragm muscles may provide additional information in case of respiratory problems.
- ✓ In individuals with Chronic Obstructive Pulmonary Disease, considering the increased muscle work to be done for respiration, entropy generation may be expected to increase further in these patients.

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