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Does the Oxygen Content of Tolkien's Middle Earth Allow for Greater Endurance?

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Abstract
The *Lord of The Rings* is a quintessential fantasy trilogy in which human men perform many seemingly unachievable feats of heroism and athleticism. One such example would be Aragorn's tireless defence of Helms Deep for an entire night. This paper investigates whether it is a feasible hypothesis to suggest that Middle Earth must have a higher oxygen content in order for the men of Rohan and Gondor to preform such physical tasks. Through using the gas exchange equation, estimating a 10% increase in atmospheric O_2 concentration in Middle Earth when compared to Earth and using Aragorn as a test subject, this hypothesis could be true.

Introduction
In J.R.R. Tolkien's fantasy series, *'The Lord of The Rings'* the humans of Middle Earth perform incredible feats of endurance. An example of this being the battle for Helms Deep whereby the human defenders fight for an entire night to maintain their stronghold against the indefatigable Uruk-Hai [1], a breed of super-orc. Assuming that the humans in Middle Earth are physiological analogues of humans on Earth then the increased endurance they exhibit could be due to external factors. One of these factors could be increased oxygen content on Middle Earth compared to that of Earth. This could also explain why creatures on Middle Earth can grow to a much larger size than they do on Earth, such as Shelob the giant spider, and how Middle Earth is home to large creatures such as dragons. This paper discusses whether or not an increase in atmospheric oxygen concentration allows for greater endurance.

Respiration
Humans require oxygen to produce ATP, the energy currency of the body. VO_2 *max* is the maximum volume of oxygen in millilitres a person can intake per kilogram of body weight per minute. The volume of oxygen a person requires for respiration increases as the effort required for the activity increases, and can continue increasing until the VO_2 *max* threshold is reached. At this point the person cannot intake more oxygen per minute.

If the effort is still increased the body begins to undertake anaerobic respiration, a product of which is lactate. The point at which the lactate exceeds the body's ability to remove it is known as the lactate threshold. Continuing to exercise past this threshold leads to lactate accumulation which reduces the pH of the surrounding tissue and gives the feeling associated with fatigue as it slows the breakdown of glucose for energy. This limits the rate at which energy can be obtained and therefore limits the energy available for the required activity.

Gas Exchange
Gas exchange takes place in the alveoli of the lungs. This process is critical to survival as it is how oxygen from the air breathed in is exchanged for carbon dioxide in the blood. This relationship is expressed in the alveolar gas equation shown by equation 1 [2]:

$$p_A O_2 = F_I O_2(P_B - pH_2O) - \frac{p_a CO_2\,(1 - F_I O_2\{1 - R\})}{R}, \qquad (1)$$

where p_AO_2 is the partial pressure of O_2 in the alveoli in mmHg, F_IO_2 is the percentage of inspired oxygen in decimal form (F_IO_2 = 0.2 on Earth), P_B is the pressure of atmosphere (P_B = 760 mmHg), pH_2O is the vapour pressure of water at body temperature and atmospheric pressure (pH_2O = 47 mmHg), p_aCO_2 is the partial pressure of CO_2 in alveoli (p_aCO_2 =

40 mmHg) and R is the respiratory exchange ratio (R = 0.8).

Presuming the atmosphere on Middle Earth has equivalent pressure to that on Earth and as mentioned the men of Middle Earth are analogous to humans on Earth it will mean all variables are the same bar the percentage of inspired oxygen, F_IO_2. On Earth this can be approximated to be 0.2 therefore any increase in this value would lead to an increase in alveolar partial pressure of oxygen. In order to see whether this oxygen is transferred to the blood the Alveolar-Arterial Gradient (*A-a gradient*) is used and is shown by equation 2 [3]. This is an established clinical equation.

$$A - a\ gradient = p_AO_2 - p_aO_2, \qquad (2)$$

where p_aO_2 is the arterial partial pressure of oxygen.

The *A-a gradient* is estimated by dividing the subjects age by four and adding four to the result, then subtracting the outcome from the calculated alveolar partial pressure of oxygen gives arterial partial pressure of oxygen. This is a well-used medical method that provides a conservative estimate and therefore sets the lowermost boundary as to what the subject's arterial partial pressure of oxygen should be [3].

Application to Endurance

The more oxygen in a person's blood, which is determined by the arterial partial pressure of oxygen, means that they will have a larger *VO_2 max* and are able to perform more aerobic respiration before beginning to accumulate lactate and start to fatigue. Therefore a rearrangement of equation 2 such that p_aO_2 (the arterial partial pressure) is calculated will be more appropriate.

The following calculations do not account for mean lung capacity, ventilation rate, or elevated levels of adrenaline and assume that the respiratory exchange ratio remains at the usual 0.8 although this can increase to as much as 1.0 during exercise.

In the case of Aragorn, whom is seen in the film as fighting near continuously throughout the battle of Helms Deep, his arterial partial pressure of oxygen can now be calculated. The oxygen content of Middle Earth will be arbitrarily assumed to be 30%, almost 10% higher than that of Earth, as this might allow for the larger creatures as mentioned in the introduction. Therefore using equation 1:

$$\begin{aligned} p_AO_2 &= 0.3(760-47) \\ &\quad - \frac{40\ (1-0.3\ \{1-0.8\})}{0.8} \\ &= 166.9\ mmHg \\ &= 22.3\ kPa \end{aligned}$$

Although Aragorn gives his age to be 87 he displays the physical prowess of a man assumed to be in their mid-thirties due to him being from a magical race of men, the Dúnedain, gifted with long life [1]. Therefore his age will be approximated to be 35 for the purposes of calculating his arterial partial pressure of oxygen.

$$Estimate\!: A - a\ gradient = \frac{35}{4} + 4 = 12.75$$

Therefore Aragorn's lowest estimated Arterial partial pressure of oxygen is:

$$166.9 - 12.75 = 154.15\ mmHg = 20.6\ kPa$$

This is 54% higher than that of the highest human range, which is between 75–100 mmHg [4]. When the same calculation is performed using the highest respiratory exchange ratio (1.0) the calculated p_aO_2 is 173.9 mmHg. This gives a range of arterial oxygen partial pressures of 154.15–161.15 mmHg.

Conclusion

Considering the normal human range for arterial partial pressure of oxygen is 75-100 mmHg [4] on Earth, the model for Middle Earth gives a lowest estimated arterial partial pressure 54% higher than the highest of the normal range (100 mmHg). This value indicates that Aragorn's superior endurance, taken as an example of a man fighting at Helms Deep, might be caused by a higher oxygen content on Middle Earth. This finding has not accounted for other factors such as mean lung capacity, ventilation rate and elevated levels of adrenaline, which are known to effect physical performance. Therefore a higher atmospheric oxygen content is shown to confer considerable physical advantage due to the higher oxygen levels in the blood, which are available to the tissues.

References

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