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THE NASAL GEOMETRY OF THE ARTIC REINDEER GIVES ENERGY-EFFICIENT RESPIRATION

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ABSTRACT

Reindeer (*Rangifer tarandus*) are exposed to harsh climatic conditions, as their distribution extends into the arctic. In winter, they might face temperatures below 233 K. Winter conditions are indeed very energetically demanding for the animal, for whom food is a very scarce resource and water is available only in the form of snow. Under these conditions, reindeer need to minimize heat and water losses. Alongside their fur with outstanding insulating properties, reindeer possess efficient thermoregulatory mechanisms that help them minimize heat loss to the surroundings [1].

The reindeer nasal heat and mass exchange mechanism plays an important role in minimizing the body heat and water which are lost upon respiration [2]. During inhalation, heat and moisture are added to the ambient air by the mucosal linings of the nasal cavity, which therefore cool down. When the warm and moist air from the lungs meets the cooler mucosal linings during exhalation, heat and moisture are then partially recovered. Previous studies have shown that the heat and water recovery capacity in animals is generally higher than in humans [3]. In particular, reindeer have evolved very complex anatomical structures in the nasal cavity (see Fig. **??**), called nasal turbinates [4]. Given the complexity of the nasal structure, it is natural to ask which role the complicated nose geometry plays in recovering heat and water during respiration.

Figure **??** represents two cross sections of the reindeer nose, taken perpendicularly to the axis of the nose. The cross sections show the scroll-type turbinate structures that characterize the reindeer nose. The mucosal lining that covers the walls and turbinates of the nasal cavity is wet by a thin layer of mucus. During respiration, water and heat are exchanged across this layer. The convolutions are less complex towards the nostrils (Fig. 1) than in the more proximal section of the nose (Fig. 2). Indeed, the nose structure is more complex towards the middle of the turbinate scroll.

Figure 1: Cross sections of a reindeer nose at 6 cm into the nose.

Figure 2: Cross sections of a reindeer nose at 10 cm into the nose.

Given the complexity of the nasal structure, it is natural to wonder if the nose geometry leads to a gradient in air flow velocity and to contact area profiles inside the nose which are beneficial for the animal in a thermodynamic sense. In particularly, we want to asses the energy recovery efficiency of the animal (1st law efficiency), as well as the amount of entropy that is produced during the breathing cycle. The entropy production of a process is indeed a measure of its thermodynamic efficiency (2nd law efficiency).

In order to answer these questions, we compare a model that mimics the real geometry of the reindeer nose with a reference case with uniform geometrical properties. In order to make the comparison meaningful, the same total contact areas and volumes are considered in the two cases. In both cases, the system is considered as composed of five interconnected subsystems as depicted in Fig. 3, which exchange mass and heat:

1. The nasal cavity is filled with air, that runs from the ambient (distal extremity of the nose) to the lungs (proximal extremity) during inhalation, and in the opposite direction during exhalation. The air is considered to be a mixture of gases, with a variable percentage of humidity. State variables are cross-section averaged. The total pressure is considered constant along the nasal cavity, and equal to the ambient pressure. The dry air is assumed to have constant molar composition (79% nitrogen and 21% oxygen), neglecting the variation in the content of oxygen and carbon dioxide and the presence of small amounts of other gases.
2. The mucus layer provides water for humidification of the air, preventing the tissues underneath from dehydration. During inhalation, cold and relatively dry ambient air enters the nose. Not all the water is recovered during exhalation, and the lost water is replaced by mucus-generating tissues (serous glands).
3. The interstitial tissues act as a capacity for storage of energy, and delay the heat exchange process.
4. Arteries and veins run through the interstitial tissues. In general, the blood flow can be regulated for thermoregulatory purposes. However, under a specific thermal condition, the flow can be assumed to be constant in time and space. The total cross section of venous vessels is 6 to 10 times larger than the one of arteries.

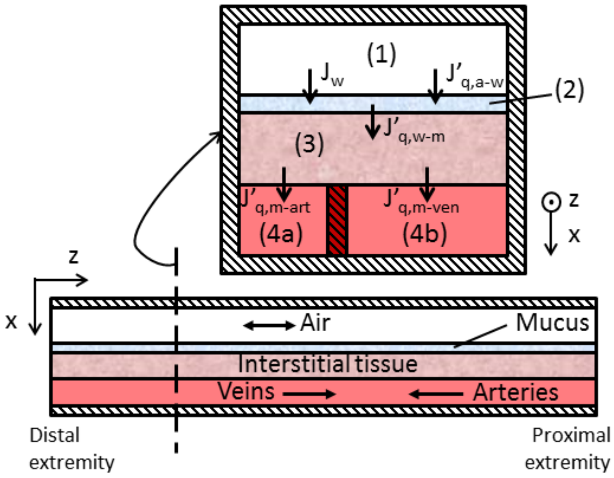

Figure 3: Illustrative representation of how the different parts of the nose interact.

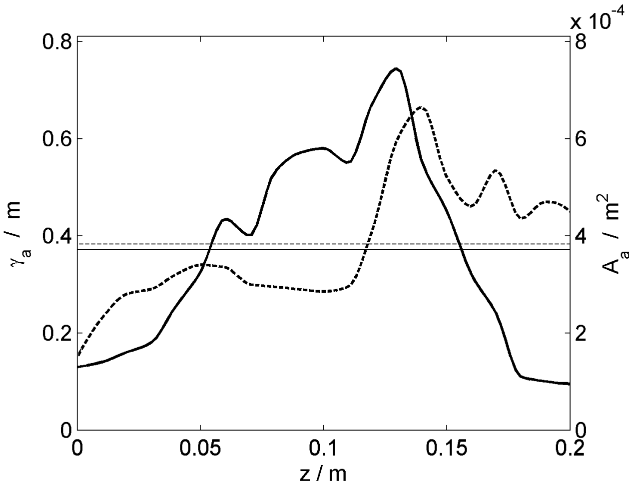

Figure 4: Cross sectional perimeter (solid line) and area (dashed line) of the nasal cavity, from the distal to proximal extremity of the nose, for the reindeer nose (thick lines) and for the reference case with uniform geometry (thin lines).

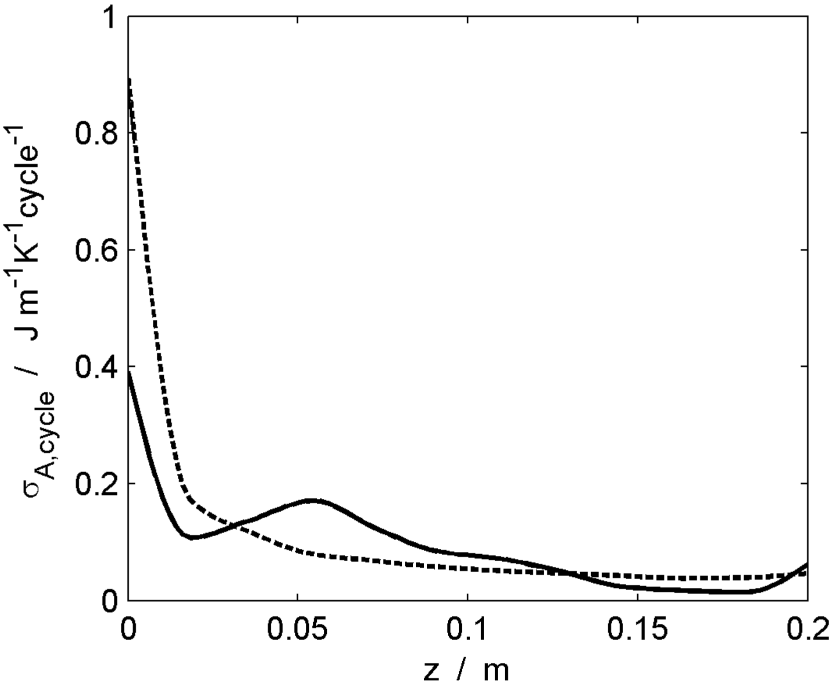

Figure 5: Comparison between the cross section entropy production of a breathing cycle, for the complex geometry model (solid line) and the reference case (dashed line). Calculations are carried out at $T_{amb} = 243$ K.

Non-equilibrium thermodynamics is used to describe the mass and heat transport between the subsystems. The performances of the two models are assessed and compared at different ambient temperatures (between 243 K and 273 K). To test the accuracy of the model, the results are compared against experimental respiration data in the reindeer that are available in literature.

The results shows that the complicated geometry of the reindeer nose has a quite large influence on the temperature and velocity profiles of the air during the breathing cycle. Most importantly, the reindeer nose allows for a lower consumption of energy during the respiration process with respect to a uniform geometry. Quite interestingly, the results indicates that the geometrical structure of the nose is more advantageous at lower temperatures. Indeed, the amount of energy which is saved with respect to the constant geometry model is larger for decreasing outside temperatures.

The same trend can be observed for the entropy production of the breathing cycle. The reduction in the total entropy production is largest at the lowest ambient temperatures. At an ambient temperature of 243 K, the reindeer nose produces 20% less entropy than the reference case. Thus, the geometry of the reindeer nose therefore appears to be more important at lower ambient temperatures, when energy efficiency is more critical for the survival of the animal. Another interesting results regards a feature of the local entropy production of the reindeer nose (Fig. 5). In the literature, an hypothesis has been proposed, stating that the most energy efficient design of a system is characterized by constant entropy production in space and time. In agreement with this hypothesis, Fig. 5 shows that the variation in the local entropy production during a breathing cycle is smaller for the reindeer nose than for the reference case. This suggests that natural selection may have favored constructions with uniform entropy production when energy efficiency is an issue.

The overall idea is that further knowledge on natural systems can inspire a more energy efficient engineering design. For the present case, the knowledge acquired from the reindeer nose can be of relevance for heat and water recuperators for the treatment of the exhausted air in the ventilation systems of buildings. Indeed, the reindeer nose and the recuperators have similar tasks and work under similar operating conditions. A similar concept has already led to the proposal of a new improved fuel cell design [5, 6].

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