Recognizing the Role of the Respiratory System in Generating Body Heat

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Abstract—**This paper critically examines the prevailing theory of how heat is generated in mammals and birds (endothermy) and puts forward an alternative hypothesis centered on the physical action of the respiratory system. The paper is based on a review of relevant literature, including observations and physical laws. The findings are that the prevailing theory of endothermy has certain weaknesses and that these weaknesses are not present in a contrasting alternative hypothesis. The author concludes that endothermy does not primarily arise from exothermic chemical reactions at a cellular level, but instead is best explained by a hypothesis based on the liberation of heat arising from the compression of inhaled air.**

Index Terms—**Endothermy, gas laws, respiratory system, thermogenesis**

I. INTRODUCTION

USEFUL advances in systems biology rely heavily on an understanding of the role and function of the relevant system involved. For example, the respiratory system is not currently recognized as playing the dominant role in generating body heat. As one researcher put it, "Nothing is more fundamental for understanding the biological nature of birds and mammals than their endothermic temperature physiology …" [1]. Since the mid 1800s, it has been accepted that heat in mammals and birds is generated by exothermic chemical processes at a cellular level. This paper posits an alternative hypothesis based on heat generation through mechanical means, namely the compression of inhaled air. Difficulties with the standard model are highlighted, followed by a selection of available evidence cited in support of this alternative hypothesis.

II. HISTORICAL PERSPECTIVE

Herman von Helmholtz (1821 - 1894) was a pioneer in the field of endothermy and thermogenesis [2]. During the mid-1800s, scientists such as von Helmholtz drew the conclusion that body heat arises because heat is liberated by chemical reactions within the body [3]. Since then, the explanation of endothermy arising as a result of exothermic chemical reactions has been regarded as settled science [4].

III. CONTEMPORARY DESCRIPTIONS OF ENDOTHERMY

The settled science which is taught to school students includes the following: "An endotherm uses heat from the chemical reactions in its cells to warm its body" [5]. Contemporary descriptions of endothermy refer to metabolism (the sum of chemical reactions within the cell), food and also physical activity, but do not mention any role played by the compression of gases. More specifically, contemporary descriptions of endothermy indicate that heat is produced through the following two mechanisms.

A. BAT and UCP1

Brown Adipose Tissue (also called BAT or brown fat) is recognized as the site of non-shivering thermogenesis. The action of an uncoupling protein (called thermogenin, uncoupling protein 1 or UPC1) found within BAT results in the uncoupling of protons moving down their mitochondrial gradient from the synthesis of adenosine triphosphate (known as ATP). As a consequence, energy is dissipated as heat [6].

B. Shivering or exercise-associated thermogenesis

Shivering is the process of simultaneously contracting antagonistic muscle pairs. This action does not produce useful locomotion. However, according to the standard model, shivering (and any other "exercise-associated" thermogenesis) gives rise to heat as a by-product of the conversion of the muscle cells' stored chemical energy (in the form of ATP) into kinetic energy. That is, the generally accepted approach asserts that, due to inefficiency in the chemical process, most of the energy is converted into the movement of muscles but some of the energy is instead converted into heat [7].

According to the standard model of endothermy, heat which has been generated by either of the two mechanisms described above is then transferred to inhaled air, in order to warm that air before it reaches the lungs. This transfer of heat from the body to inhaled air apparently occurs in the nasal passages, presumably by convection, conduction, radiation or some combination of all three processes.

A synopsis of technical expertise in the field of in vivo nasal air conditioning published in 2010 concluded that the complex three-dimensional anatomical structure of the human nose makes it impossible to perform detailed in vivo studies on intranasal heating within the entire nasal airways applying various technical set-ups [8]. According to this synopsis, in vivo measurements within the entire nose are not feasible. In other words, even under modern laboratory conditions, actual comprehensive measurements of air being heated inside the nose – which would illustrate the mechanism of supposed heat transfer from nasal passages to inhaled air – is still not achievable, leaving untested a key element of the standard model of endothermy.

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IV. PROBLEMS WITH THE STANDARD MODEL

There are several problems with an approach which relies primarily upon BAT and UCP1 as the main source of heat production in endotherms. Four of these are summarized below:

(i) Pigs are endotherms. However, pigs do not have BAT [9].

(ii) Birds are endotherms. However, birds do not have BAT and birds lack the gene for UCP1 [10].

(iii) The gene for UCP1 is present in fish and amphibian species which do not exhibit endothermy [11].

(iv) Infants have more prominent BAT than adult humans [12]. However, infants display a reduced ability to regulate their body temperature compared to adults.

The above four points tend to cast doubt upon a model centered on heat production via BAT and UCP1. Relying on movement as the secondary source of heat production in endotherms is also problematic. Two relevant points are as follows:

(i) Some rodents and bats shiver as their body temperature rises when they emerge from hibernation. Likewise, certain python species shiver to raise their body temperature when brooding [13]. However, apart from these isolated examples, shivering is a comparatively uncommon activity.

(ii) If the mere action of causing muscles to contract is sufficient to generate heat - through an inefficient conversion of chemical energy into kinetic energy - then it appears logical to expect that muscle contraction in fish, amphibians and reptiles would also display an equivalent exothermic effect. Very active monitor lizards, for example, may walk up to four kilometers per day [14] and salmon swim many times this distance. However, despite the muscular action involved, these animals are not recognized as exhibiting endothermy. In other words, the standard model fails to explain why movement in fish, amphibians and reptiles does not generate heat on a similar scale to that observed in mammals and birds.

An additional problem with the standard model of endothermy is that air is not noted for its ability to conduct heat. Air has a thermal conductivity in the order of 0.024 W/(m K) [15]. This compares to a thermal conductivity of 0.58 W/(m K) for water and 401 W/(m K) for copper. Also, air typically flows through an adult human’s respiratory system at a rate of approximately 7.5 liters/minute. Consequently, for heat to be transferred from the body to inhaled air (by convection, conduction and/or radiation) such that the temperature of the air is raised from ambient temperature to around 36.9 degrees Celsius, this would tend to require super-heated elements within the nasal passages. To date, no such elements have been identified.

V. THE NEW HYPOTHESIS OF AIR SQUEEZING

By contrast to heat generation through an exothermic chemical process at cellular level, this paper puts forward the hypothesis that the dominant process through which mammals and birds generate heat is by squeezing inhaled air. The standard model of endothermy is silent on air pressure changes within the respiratory system. By contrast, if it is accepted that the inhaled air is compressed, then the generation of body heat can readily be accounted for as a simple consequence of an adiabatic process.

Expressed in its highest terms, this paper posits that in mammals and birds, inhaled air acts as a compressible compression element in a tensional integrity system. However, even a basic grasp of fundamental physics is sufficient to illuminate the mechanism of heat production through a squeezing of air by mammals and birds. That is, this paper looks to physics rather than chemistry as the key to understanding endothermy.

VI. VENTURI EFFECT AND THE GAS LAWS

The respiratory tract has openings, narrowing and widening, both relatively fixed and subject to variation by muscular control. Gross volume change is also imposed by action of the primary and accessory muscles of breathing, such as the respiratory diaphragm and intercostals.

The Venturi Effect describes the impact on the pressure of a gas when it flows through a tube of varying dimensions. That is, all other things being equal, when the tube becomes wider, the gas pressure increases. By contrast, when the gas is made to flow through a narrower section, the gas pressure decreases.

The Ideal Gas Law describes the relationship between pressure, volume, temperature and number of representative particles of a gas. This is built upon Boyle's Law, Charles' Law, Gay-Lussac's Law, Avogadro's Law and the Combined Gas Law. In other words, the behavior of gases is a well understood area of physics.

Despite this good understanding of physical laws regarding the consequences of squeezing a gas, the standard model of endothermy ascribes the change in temperature of inhaled air to the transfer of heat derived from exothermic chemical reactions. Rather than ignoring these gas laws, the hypothesis put forward in this paper accepts that inhaled air is governed by the same processes which affect any gas and that heat is liberated by pressure and volume changes imposed by the action of the respiratory system on inhaled air.

It is beyond the scope of this paper to provide a primer in applied fluid dynamics in a biological setting. However, as a simplification for illustrative purposes, it is useful to consider how much of a squeeze is required to elevate the temperature of a fixed volume of air.

A simple way of translating pressure difference into everyday experience is to make reference to weather reports. On any given day, there could be a low pressure cell over Los Angeles with a value of 972 millibars and at the same time a high pressure cell over New York at 1032 millibars. This 60 millibar difference in atmospheric pressure would be virtually imperceptible to humans. However, if a squeeze of 60 millibars is applied by the body to a fixed volume of 6 liters of air (the average total lung capacity of an adult male), this would be sufficient to raise the temperature of that air from 18.9 degrees Celsius to 36.9 degrees Celsius (normal human body temperature). For completeness, it is noted that the volume of air in a living person’s respiratory system is not fixed and that $P_1/T_1 = P_2/T_2$ calculations are not influenced by how many liters are involved, provided that the volume remains constant.

The hypothesis advanced in this paper depends upon the impact of applying pressure to inhaled air, which occurs when air becomes part of a system of high tensional integrity. The author suggests that the greater difficulty is explaining how air can be passed through the respiratory system of a mammal or bird without changes in pressure, or if it is conceded that pressure changes do occur, how those pressure changes can be achieved without coincident changes in the observed temperature of that air.

VII. NASAL CONCHA

Certain morphological arrangements and structures give rise to a physical distinction between the respiratory system of endothermic animals and other animals. The most obvious of these differences is the presence of nasal concha, also known as respiratory turbinates, in most mammals and birds. Structures of the same level of complexity are not found in fish, amphibians and reptiles [16]. Inhaled air flows through the nasal concha, which are defined by their spiral or cork-screw shape. The presence of turbine structures within the respiratory system is suggestive of a key role in the pressurization of inhaled air. This is supportive of a hypothesis linking the application of pressure to inhaled air in mammals and birds to the generation of heat in those animals.

There are some exceptions to the general rule that fish, amphibians and reptiles do not display endothermy. The leatherback turtle (*Dermochelys coriacea*) is a species which displays some degree of endothermy. In leatherback turtles, the upper respiratory tract has a vascular lining which appears to be a simple analog of the complex turbinates of mammals and birds [17]. This observation tends to support a hypothesis based on the involvement of physical structures in endothermy.

VIII. OVERCOMING THE PROBLEMS IDENTIFIED WITH THE STANDARD MODEL

The approach to endothermy proposed in this paper does not suffer from the same problems identified above in respect of the standard model. That is:

(i) The new hypothesis explains why pigs display endothermy despite the absence of BAT. Pigs can still apply pressure to inhaled air, regardless of their lack of BAT.

(ii) The new hypothesis explains why birds display endothermy despite the absence of BAT and UCP1. Birds can still apply pressure to inhaled air, regardless of their lack of BAT and lack of UCP1.

(iii) The new hypothesis explains why the presence of the gene for UCP1 in fish and amphibian species is not sufficient for them to display endothermy like mammals and birds. Despite having the gene for UCP1, fish and amphibians do not have the morphology necessary for the application of pressure within their respiratory system.

(iv) Juvenile birds and mammals, including human babies, commonly exhibit reduced capacity in respect of heat generation compared to when more mature. If, as the standard model suggests, heat generation in humans is simply an exothermic chemical process at the cellular level, then it is difficult to explain why this chemical process could not be equally well controlled by an infant as an adult. That is, new-born infants effectively manage other cellular chemical processes, such as those required for digestion and assimilating oxygen. This appears to be a particular conundrum given that, as noted above, infants have more prominent BAT than adult humans. However, if the predominant source of heat production in endotherms is instead an air-squeezing process, involving coordinated contractions of muscles, ligaments, bones and related structures within the body, then it is readily understandable that a new-born infant will not be adept at achieving this. Only later, when physical control is improved and physical structures have matured, could such a process be mastered.

(v) The comparative rarity of shivering suggests that a model of endothermy based in part on the muscle-firing aspect of this activity is not a generally applicable model. However, the new hypothesis explains why, under extreme conditions, the coordinated contraction of antagonistic muscle pairs is a useful addition to the process of thermogenesis. It is submitted that such muscular contractions serve to intermittently increase pressure on the air in the respiratory system, thus liberating additional heat in times of extreme demand.

(vi) The standard model relies in part on the concept of exercise-associated thermogenesis, whereby the mere action of causing muscles to contract is sufficient to generate heat, due to an inefficient transfer of chemical energy to kinetic energy. As noted above, the standard model fails to explain why muscle movement in fish, amphibians and reptiles does not generate heat on a similar scale to that observed in mammals and birds. By contrast, the new hypothesis explains why an increase in exercise in mammals and birds – resulting in faster respiratory turnover and therefore an increased opportunity for squeezing of inhaled air - generates additional body heat, whereas such an effect does not generally occur in fish, amphibians and reptiles, which have a morphologically different respiratory system.

(vii) The new hypothesis does not rely on inhaled air being warmed by convection, conduction or radiation. This accounts for the absence of observed super-heated elements within the respiratory system of mammals and birds.

IX. D-I-Y, LONG-STANDING PRACTICES AND EXTREME EXAMPLES

That muscular control over elements of the breathing process is sufficient to manipulate air temperature can be readily observed by any reader of this paper. To demonstrate, as a first step, breathe out through tightly pursed lips onto your palm. The second step is to breathe out with a wide open mouth onto your palm, as if trying to fog up a mirror. Heat sensitive cells within the skin of your palm will confirm that these two techniques give rise to cooler and warmer air temperatures respectively.

Refinements of breathing techniques and physical alignments for heating or cooling purposes are preserved in various long-standing practices (such as in chi gung, pranayama and other related techniques [18]). The air squeezing hypothesis set out in this paper provides a simple explanation of endothermy which is consistent with these practices. Similarly, the well-documented ability of certain individuals to demonstrate extreme feats of thermogenesis – such as Wim Hoff [19] and some Buddhist monks [20] – is readily understood when it is recognized that the key operational factor is attention to the mechanics of breathing.

TABLE I
PARADOXES OF THE PREVAILING THEORY OF ENDOTHERMY COMPARED TO THE HYPOTHESIS PUT FORWARD IN THIS PAPER

Factor	Accounted for by prevailing theory (endothermy from BAT, UCP1 and inefficient muscle contraction)	Accounted for by the hypothesis in this paper (endothermy from squeezing of air)
Pigs lack BAT, but are endotherms	X	✓
Birds lack both BAT and UCP1 gene, but are endotherms	X	✓
Fish and amphibians have UCP1 gene, but are not endotherms	X	✓
Infants have more prominent BAT, but cannot regulate temperature as well as adults	X	✓
Shivering is relatively uncommon	X	✓
Muscle contraction in fish, amphibians and reptiles does not produce endothermy	X	✓
Air is a poor conductor of heat	X	✓

X. GENERAL DISCUSSION AND EVALUATION

Commentators have observed that certain breathing practices can generate excessive body heat via an as yet unexplained mechanism [21]. Engineers bring a unique perspective to their consideration of the respiratory system, due in part to their familiarity with physical laws such as those regarding thermodynamics. For example, engineers are aware that an adiabatic process is not something to do with diabetes. In their search for solutions and explanations, engineers tend not to be constrained by obedience to historic authority, but instead have a strong objective sense of reality. This scientifically-minded approach yields dividends in the re-consideration of the true source of body heat.

Implications of the new understanding outlined in this paper extend to topics such as metabolism. The bulk of food energy ingested by mammals and birds has long been understood to be consumed in the process of generating body heat. Until now, that process was assumed to be a chemical one. However, in line with the laws of thermodynamics, this paper contends that food energy is used by mammals and birds to do work on inhaled air, raising the temperature of that air, which then warms the body as heat dissipates from within the respiratory system. This new understanding therefore offers fresh insights into the energy balance of endotherms, such as is relevant to obesity.

At the practical level of the individual, the air squeezing hypothesis explains how conscious control over the physical components of the respiratory system can be used to alter body temperature. Awareness and cultivation of this mechanism may prove useful in situations where the prevailing temperature poses a risk of hypothermia or discomfort.

At a population level, if humans adopt a more informed approach to generating body heat and maintaining their body temperature, then this will result in less reliance on external sources of heat. At present, such external sources of heat are generated primarily by fossil fuels. Less reliance on external sources of heat should therefore result in decreased carbon dioxide emissions.

Recognizing the role of the respiratory system in generating body heat illustrates the substantial benefit of bringing an engineering perspective to the field of systems biology. As noted above, there are major positive implications to this step forward. It is intended that this paper will serve as a starting point in a new direction of research. Further study is required to add rigor to the thermodynamic analysis, which to date is under-represented in the evidence base, primarily due to the prevailing focus on chemistry rather than physics in the consideration of endothermy.

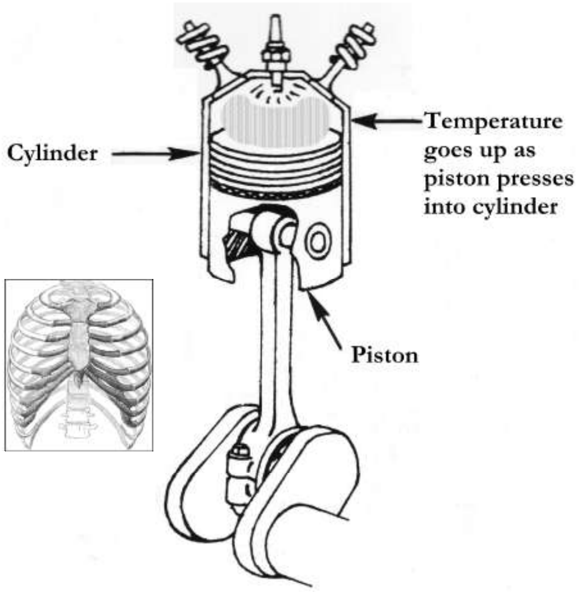

Fig. 1. Piston compressing gas in a cylinder. This paper contends that the same laws of thermodynamics which apply to gas in a cylinder also apply to air within the bounds of the respiratory system. As the piston pushes into a cylinder, the temperature of the contained gas rises, which is an approximation of an adiabatic process (adapted from an image released into the public domain by the copyright holder Pearson Scott Foresman [22]). Inset: Human rib cage. The rib cage represents a boundary of the respiratory system, within which pressure can be applied to inhaled air, thereby raising its temperature (adapted from an image now in the public domain from H. Gray (1918) *Anatomy of the Human Body* [23]).

XI. CONCLUSION

This paper advances the hypothesis that mammals and birds produce heat by compressing air within the respiratory system. Whilst such heat generation requires chemical energy, it is not a simple exothermic chemical reaction (essentially free of mechanical requirements) as previously assumed. Between chemical energy and heat, this new approach posits that there is an intermediate step involving a mechanical process. This intermediate step is the compression of inhaled air which results in heat being liberated. Based on a survey of the available evidence, the author submits that the air squeeze hypothesis compares well to the long-accepted standard model of endothermy. The air squeeze hypothesis has profound implications for our understanding of physiology and medicine, including issues such as the energy balance equation of metabolism, regulation of body temperature, the functional difference between upper and lower vertebrates, and the role of the respiratory system beyond the exchange of oxygen and carbon dioxide.

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