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Introduction

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What is physiologging? Introduction to the theme issue, part 2

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The physiological mechanisms by which animals regulate energy expenditure, respond to stimuli and stressors, and maintain homeostasis at the tissue, organ and whole organism levels can be described by 'physiologging'—that is, the use of onboard miniature electronic devices to record physiological metrics of animals in captivity or free-living in the wild. Despite its origins in the 1960s, physiologging has evolved more slowly than its umbrella field of biologging. However, the recording of physiological metrics in free-living animals will be key to solving some of the greatest challenges in biodiversity conservation, issues pertaining to animal health and welfare, and for inspiring future therapeutic strategies for human health. Current physiologging technologies encompass the measurement of physiological variables such as heart rate, brain activity, body temperature, muscle stimulation and dynamic movement, yet future developments will allow for onboard logging of metrics relating to organelle, molecular and genetic function.

This article is part of the theme issue 'Measuring physiology in free-living animals (Part II)'.

1. Introduction

Physiology is the science of life, and can be broadly defined as a branch of biology that aims to understand the internal mechanisms that allow living things to stay healthy and respond to the challenges of everyday life. Physiological research spans a wide range of variables from the basis of cell function at the ionic and molecular level, to the integrated response of the whole organism and the influence of the external environment. In the context of 'biologging' research [1–4], the sub-discipline of 'physiologging' is defined here as 'the recording of physiological metrics (e.g. metrics that describe causality, homeostasis and energy expenditure) onboard miniature electronic devices carried by animals both in captivity and at liberty in the wild' (figure 1). Physiologging does not include analyses of physiological variables *ex situ* (e.g. processing a blood sample in the field with a hand-held instrument, or bringing an animal to a measurement device not mounted on or in the animal), but instead the data are logged onboard the animal (although the animal need not be in the wild, see [5]). In this context, it is important to define which variables can be considered as 'physiological' so that developments and evolution in this field can be measured. Generally speaking, physiologging is *not* considered to include metrics that describe the three-dimensional location or orientation of an animal (e.g. GPS or satellite location, dive depth or flight height, magnetic direction etc.), but rather includes a suite of sensors or metrics that measure cellular, chemical and systemic (e.g. cardiovascular and respiratory) changes that describe how an animal functions in response to environmental and/or anthropogenic stimuli (table 1, see [37,38]). Often, physiologging is combined with behavioural information, such as location tracking, and in these cases offers some of the strongest insights into the coupling between physiological mechanisms and resulting behaviours (see [22,39–41]).

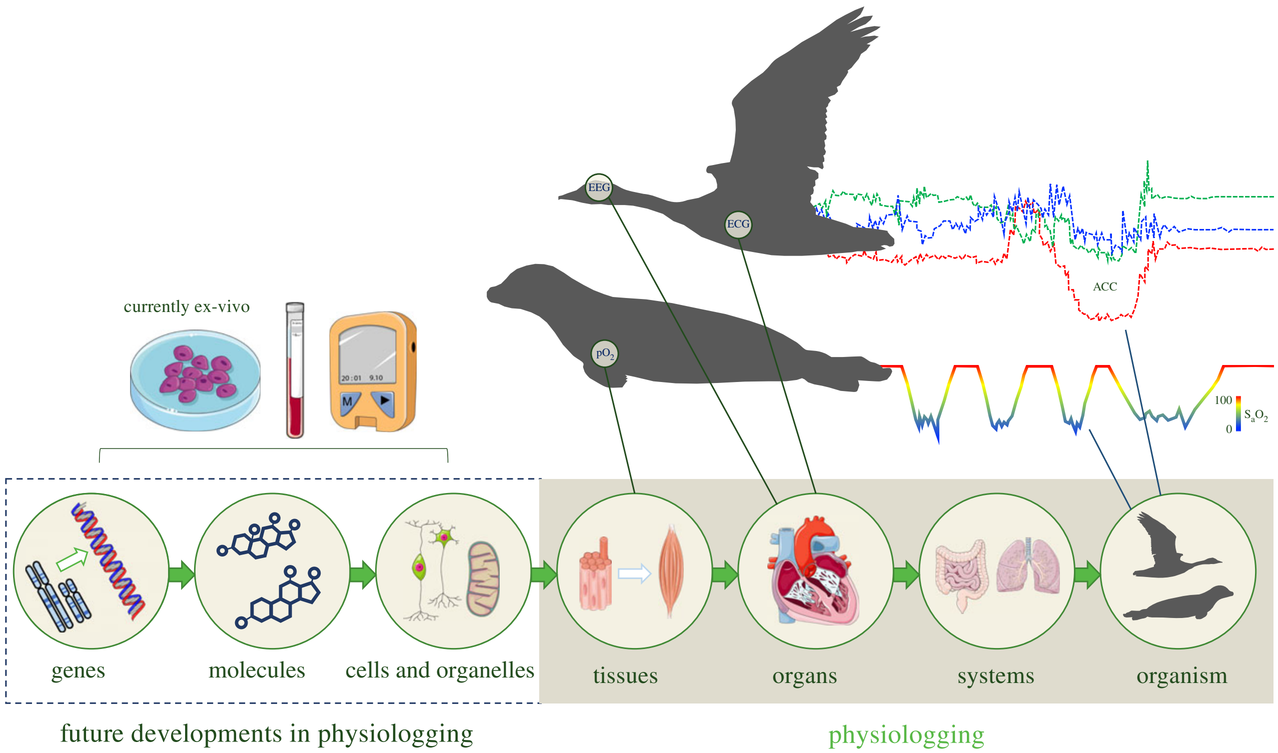

Figure 1. Physiologging involves recording physiological metrics onboard miniature electronic devices carried by animals both in captivity and at liberty in the wild. Current physiologging technologies are capable of recording physiological metrics at the tissue, organ, system and whole organism levels (beige shaded area), but future developments will allow for onboard logging of metrics relating to organelle, molecular and genetic function (dashed box). ACC, acceleration.

Table 1. Description of some physiologging metrics.

variable	value of approach	examples
heart rate (ECG), variability and waveform characteristics	cannot expend energy without paying cardiovascular costs at some temporal scale	[6–10]
accelerometry (1-, 2- or 3-axes)	dynamic acceleration must be funded by muscular contraction with associated metabolic cost	[11–14]
body temperature	reveals patterns of diurnal behaviour, exercise thermogenesis and seasonal changes in homeotherms may be correlated with metabolic rate in heterotherms (following principles of Q_{10})	[15–18]
partial pressure of O_2 (pO_2)	can predict blood O_2 saturation as haemoglobin binds to O_2 in relation to pO_2	[19–21]
brain activity (EEG)	directly measures neural transmission of stimuli perception and response	[22–24]
compounds in the blood (e.g. glucose, lactate, hormones)	provides insights into physiology, pharmacokinetics, toxicology of drugs and metabolites	[25–27]
ventilation (rate, tidal volume)	most air-breathing animals cannot acquire O_2/release CO_2 without ventilation	[28,29]
muscle movement (EMG)	measures motor unit action potentials of muscle groups, with associated metabolic costs	[30,31]
gastric pH	pH increases as prey is ingested, and decreases as gastric acids and enzymes are secreted for digestion	[32,33]
tissue blood flow and oxygenation	blood flow is managed to deliver O_2 and remove CO_2 depending on metabolic demand	[34–36]

In this special issue, we feature some of the latest examples of physiologging in a range of animal systems to demonstrate the breadth of research questions and insights that this exciting field can produce. Arguably, the first and most fundamental physiologging metric is the recording of heart rate, which dates back as far as 1962 in birds [42], 1968 in fish [43] and 1972 for pinnipeds [44]. This metric has been successfully used to demonstrate some of the more astonishing accomplishments of free-living animals, for example, that diving whales can have heart rates as low as 2 beats per minute [45], whereas on the opposite end of the spectrum, flying birds can maintain heart rates of more than 500 beats per minute for many hours [46,47]. The rapid development and increasing availability of technologies capable of monitoring and analysing heart rate in recent times [6] have been used to gain unique insights into animal welfare (e.g. farmed terrestrial and aquatic species [48–51]), to assess social interactions in animals [52–55] and to comprehensively understand the cardiorespiratory adaptations of breath-hold diving species [7,8]. A more recent physiologging variable is accelerometry, where the two- or three-dimensional acceleration of an animal is recorded at a temporal resolution that is sufficiently high to reveal individual wing or tail beats during locomotion [56–59]. Although accelerometry does not directly measure energy expenditure, dynamic body acceleration has often been shown to be correlated with energy expenditure when the animal is in its primary mode of locomotion [60,61]. When used judiciously, accelerometry has revealed fascinating insights into the costs of movement in a range of species [62]. Physiologging of body temperature has also been widely used throughout the terrestrial and aquatic realms [63], and can yield broad insights into the activity patterns and behaviour of free-living animals [15–18,64]. Another commonly used physiologging metric is the intravascular partial pressure of O_2 (pO_2), which requires the use of highly specialized equipment and techniques (and has thus been restricted to just one extended laboratory of researchers). However, this metric has provided a foundation for much of what we know about diving physiology and oxygen management (see [65]). Finally, the recording of brain activity has revealed astonishing insights into cognition, navigation and sleep in both wild and captive animals [22,23,39], with advanced loggers currently as small as 1.92 g commercially available at the time of writing (see https://www.vyssotski.ch). Currently, there is comparatively little work in animal physiologging on circulating compounds in the blood, despite the fact that an automated blood sampling device was first envisaged and built in 1986 [66]. This device was further refined recently and a current version measures 18 × 8.6 cm, weighs 160 g in water and is capable of drawing two blood samples during deployment [67]. Furthermore, a technology from the biomedical field has been adapted to provide continuous, non-invasive measurements of blood flow and tissue oxygenation through Near Infrared Spectroscopy technology [34,35], and the future adaptation of medical technology will permit measurements of circulating chemicals in an animal's tissues. For example, the measurement of various hormones and metabolic substrates, without the need for sampling and storage of blood, is now commonplace in human wearable technologies [68,69].

As the future brings about significant changes in climate and anthropogenic pressure on biodiversity [70–72], physiologging will fundamentally underpin our understanding of how to predict biodiversity responses and to set appropriate conservation policies [73,74]. Indeed, measuring physiology in free-living animals will underpin a huge range of future research priorities from understanding the potential of animals to tolerate and adapt to rapidly changing environments, to managing invasive species, to understanding the impact of threats such as pollution, for ensuring the success of restoration efforts and for managing human–wildlife interactions [75]. Physiologging will also be key for understanding the mechanisms with which vertebrate life copes with extremes of hypoxia, circulatory changes and infectious diseases, which will undoubtedly have important ramifications for future medical interventions in humans [76,77]. Many of these research questions will need to be tackled outside of the laboratory in wild animal study systems, and thus physiologging technologies perhaps provide the most critical tools for future biodiversity research.

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