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Current Status and Potential Applications of Wearable Biosensors in Wildlife Monitoring: Implications for Tibetan Antelope Monitoring

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Abstract. In the context of today 's increasingly severe challenges to global wildlife protection, this paper reviews and comments on the latest progress of intelligent wildlife monitoring technology. The research focuses on the innovative application of wearable biosensor technology in wildlife monitoring, and especially discusses the significant potential of wearable biosensors in improving monitoring accuracy and data dimension from human use to wildlife application. Taking the ' food hypothesis ' that has long existed in the study of seasonal migration behavior of Tibetan antelope as a specific case, this paper designs a wearable biosensor device dedicated to this species. The device can continuously collect multi-dimensional physiological data such as heart rate and body temperature, and can also judge the nutritional status of Tibetan antelope through nutritional markers in the blood. In order to provide an objective and continuous empirical basis for verifying the migration-driven hypothesis, this technical solution not only deepens the understanding of the ecological behavior of Tibetan antelope, but also further promotes the monitoring and protection of wild animals to the direction of intelligence, data and precision.

Keywords: biosensor, wildlife, ecology, rapid testing

1. Introduction

In the context of today 's increasingly severe challenges to global wildlife protection, this paper reviews and comments on the latest progress of intelligent wildlife monitoring technology. The research focuses on the innovative application of wearable biosensor technology in wildlife monitoring, and especially discusses the significant potential of wearable biosensors in improving monitoring accuracy and data dimension from human use to wildlife application. Taking the ' food hypothesis ' that has long existed in the study of seasonal migration behavior of Tibetan antelope as a specific case, this paper designs a wearable biosensor device dedicated to this species. The device can continuously collect multi-dimensional physiological data such as heart rate and body temperature, and can also judge the nutritional status of Tibetan antelope through nutritional markers in the blood. In order to provide an objective and continuous empirical basis for verifying the migration-driven hypothesis, this technical solution not only deepens the understanding of the ecological behavior of Tibetan antelope, but also further promotes the monitoring and protection of

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wild animals to the direction of intelligence, data and precision. 1Introduction Today, wildlife conservation is facing unprecedented challenges. Globally, human activities and climate change have made it more difficult for researchers to find traces of wild animals. The decrease in the number of wild animals has also prompted us to pay more attention to each individual wild animal, which makes wildlife monitoring technology need to be more perfect and refined. Biosensors can play a big role in this case. Wildlife monitoring technology refers to the method of collecting wildlife activities and traces to obtain their specific information. For wild vertebrates, the traditional survey method is usually to collect evidence of animal entities or occurrences through sample line and sample survey. In recent years, there have been some efficient monitoring techniques with little interference to animals [1]. Biosensor is an independent integrated device that can provide specific quantitative or semi-quantitative analysis information using a biometric element that is in direct spatial contact with the transduction element (IUPAC, 1996). Such devices mainly rely on the molecular recognition function of bioactive materials such as proteins, enzymes, and nucleic acids to convert microscopic biological processes such as conformational changes and concentration changes of the substances to be tested into electrical signals for quantitative analysis and intuitive observation. Wearable computers are wearable micro-electronic devices that can be worn on the body to go out and carry out activities. Nowadays, they often appear together with biosensors as information processing. This paper intends to summarize the existing biosensor technologies that can be used for wildlife monitoring, and on the premise of wearable, design a biosensor that can be applied to Tibetan antelope to monitor the dynamic and physiological indicators of Tibetan antelope to solve the corresponding specific problems.

2. Existing biosensor technologies

In recent years, wildlife monitoring has been advancing towards intelligent and automated systems. Certain biosensor technologies currently deployed for human applications can also be adapted for wildlife monitoring.

2.1. DNA barcoding technology

DNA barcoding is a method for species identification utilising short DNA fragments derived from specific genes or multiple genes. Its fundamental principle involves comparison with reference DNA fragment libraries of known species, occasionally enabling the identification of unknown species or tissue samples from organisms [2]. It is necessary to develop bar code methods of different scale types for different identification requirements or different application scenarios. DNA barcodes are mainly divided into conventional barcodes, mini barcodes and super barcodes according to the sequence length. Conventional barcodes have high specificity in identifying freshly collected or well-preserved samples. They can identify relevant components in synthetic products and play a role in preventing commercial fraud, identifying endangered species, and protecting consumer health [3]. A 2022 study demonstrated DNA barcoding's efficacy in distinguishing traditional Chinese medicinal materials by identifying "specificity barcodes" at different scales, effectively eliminating quality control and adulteration issues [4]. DNA barcoding technology boasts broad applicability and high identification accuracy. In the foreseeable future, it is expected to integrate with techniques such as machine learning to uncover additional applications beyond current species identification functions, including . However, DNA barcoding currently demands high sample integrity, which hinders fieldwork implementation.

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2.2. DNA metabarcoding

DNA metabarcoding is similar to dna barcoding, which requires DNA extraction, PCR amplification, sequencing and data analysis in turn, but does not focus on a specific organism, but aims to determine the species composition in the sample. Multiple associated species can be identified from one sample. A study conducted by the National Key Laboratory of Livestock and Poultry Nutrition and Feeding, College of Animal Science and Technology, China Agricultural University in 2024, extracted DNA from Tan sheep feces samples, and used ITS2 barcode and fDNA metabarcoding to quickly analyze the species composition in feces based on the two indicators of frequency of occurrence (FO) and relative read abundance (RRA). It is proved that the fecal DNA metabarcoding technology based on ITS2 fragment is feasible in the rapid and accurate feeding habits analysis of herbivorous livestock [5]. This approach also holds significant importance for investigating the diets of wildlife populations. Its low demands on sample integrity and capacity to process large quantities of DNA in a single run render it particularly valuable for field surveys.

2.3. Third-generation gene sequencing

Third-generation sequencing (TGS) technology offers high throughput, long read lengths, and enables direct sequencing of amplification-free DNA. It facilitates direct sequencing of DNA or RNA, eliminating preliminary reverse transcription and amplification steps, overcoming read length limitations, and achieving full-length sequencing [6]. Based on Oxford Nanopore 's TGS technology, the detection equipment developed by minION in recent years can achieve rapid detection with a palm-sized detection device. It can make DNA detection not limited to the laboratory, portable and fast, and can be detected immediately after collection in the field to improve timeliness. However, there is still a situation where the accuracy is lower than that of traditional DNA detection technology.

2.4. Rapid trace element detection

There are some differences in the detection methods for various trace elements in the human body. Here is an example of the detection of vitamin a and iron required for the sensor in this paper : antibodies are often used to detect proteins with trace elements in samples, such as iron. When detecting iron, it is generally detected for ferritin. Cornell University integrated three antibodies in a test paper in a 2017 study for the detection of vitamin a and iron deficiency at the nursing site to achieve the purpose of screening for night blindness. This method is fast and cheap, but it also has poor accuracy [7].

3. Biosensors for the Tibetan antelope migration-food hypothesis

3.1. Rationale

Tibetan antelope (scientific name : Pantholops hodgsonii), known as Tibetan antelope, is the only species of the genus Pantholops in the subfamily Antelope. Its back is reddish brown, and its abdomen is light brown or grayish white. The habitat of Tibetan antelope is 3250 ~ 5500 meters above sea level, which is most suitable for the flat terrain around 4000 meters above sea level. It is an endemic species in China. Tibetan antelope is considered to have seasonal migration behavior. Scholars have many speculations about what causes the female Tibetan antelope to migrate long distances to fixed areas to give birth. One is the food hypothesis. The food hypothesis holds that ;

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the food in the birth place may be rich in trace elements and proteins that are beneficial to fetal growth and maternal milk production, or the water source in the birth place is beneficial to the survival of female Tibetan antelope and its pups [8].

The nutritional value of the plant species that the Tibetan antelope actually feeds in the lambing area is not as different as it is supposed to be compared with the wintering area.

If only for food, it is difficult to explain why Tibetan antelope have to risk huge energy consumption and risk (such as crossing roads, railways, encountering bad weather) Consequently, the food hypothesis alone appears insufficiently explanatory. To further investigate and validate the food hypothesis for Tibetan antelope migration, physiological data from female antelopes across different habitats and time periods would be required.Traditional track-based research methods suffer from poor timeliness, permitting investigation only after sample collection, while also facing risks of sample damage or loss. While radio collars or infrared camera technology alone can help determine the location of target Tibetan antelopes, they cannot directly obtain physiological data. Specially designed biosensors can therefore resolve this issue.

3.2. Sensor principles

Trace elements and specific fatty acids (such as Omega-3) in Tibetan antelope blood serve as nutritional biomarkers. These two indicators can be used to assess the nutritional status of Tibetan antelope. Their advantage lies in their constant presence in Tibetan antelope blood, where changes in their concentrations reflect the quality of the antelope's diet. Furthermore, these substances are difficult for Tibetan antelope to synthesise internally.

Principle of fatty acid measurement via near-infrared spectroscopy: Chemical bonds such as C-H, O-H, and N-H in organic compounds exhibit characteristic absorption in the near-infrared region. Differences in the chemical structures of various fatty acids result in distinct near-infrared spectra. By establishing mathematical models correlating spectral data with actual fatty acid content measured by standard methods (e.g., GC), NIRS enables rapid prediction of fatty acid composition in new samples. The process broadly involves the following steps.First, collect a large number (typically hundreds) of representative Tibetan antelope blood samples. Simultaneously, scan these samples using NIRS to obtain their spectra, then precisely determine their fatty acid composition using traditional GC methods. Employ chemometric software to establish a calibration model linking the spectral data to the GC measurements. For new, unknown samples, a single NIRS scan suffices; the instrument's built-in model can predict the content of various fatty acids within tens of seconds.

Guilherme L. Menezes et al. demonstrated the feasibility of this approach in a 2024 study, confirming that NIR spectroscopy could serve as a tool for detecting cows under severe NEB, leading to lipid mobilisation from adipose tissue into non-esterified fatty acids (NEFA). The research also indicated potential for broader application throughout the entire transition period, as the spectral signal carried relevant information regarding cow metabolism [9].

For trace element analysis, existing techniques enabled by combining multiple fluorescent markers and immunoassay approaches on a single test allow us to provide accurate quantification within 15 minutes, even though the physiological range of the markers of interest varies over five orders of magnitu itude. We report sensitivities of 88%, 100%, and 80% and specificities of 97%, 100%, and 97% for iron deficiency (ferritin <15 ng/mL or 32 pmol/L), vitamin A deficiency (retinol-binding protein <14.7 μg/mL or 0.70 μmol/L) and inflammation status (C-reactive protein >3.0 μg/mL or 120 nmol/L), respectively. ([7]) Precision and miniaturisation meet research requirements

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4. Sensor design

The purpose of this study was to explore the use of wearable devices specifically modified by Tibetan antelope to monitor the physiological markers of Tibetan antelope. The device is based on a wearable blood detection device used by humans. The integrated fixture, micro-blood collection equipment, enrichment structure, detection equipment and satellite transmission equipment were installed after anesthesia of the female Tibetan antelope participating in the migration. Micro-blood samples were regularly obtained from subcutaneous capillaries of female Tibetan antelope, and their nutritional markers were detected after preliminary separation and enrichment by microfluidic structure. Among them, the fatty acids in the blood are used by infrared spectroscopy, that is, the infrared spectroscopy data of Tibetan antelope blood with a large number of different fatty acid contents are trained to form a database, and then the data detected by the wearable device are compared with the database to obtain the fatty acid content in the blood of Tibetan antelope. The carriers of various trace elements in the blood were detected using specific enzymes. After the results are obtained, the data are transmitted to the researchers through the satellite network to realize the real-time monitoring of the nutritional markers of wild female Tibetan antelope before and after the entire migration, which helps to better verify the hypothesis.

In view of the differences between Tibetan antelope and humans, existing wearable devices may need to make some modifications to adapt to female wild Tibetan antelope. For example, considering the body characteristics and long hair coverage of Tibetan antelope, the equipment fixings are made of elastic materials to ensure comfortable fit and not easy to fall off. The length and angle of the blood sampling probe are specially designed to accurately collect trace blood samples through thick hair. The overall weight of the equipment is controlled within 150 grams, which is only about 0.4 % of the weight of Tibetan antelope, so as to avoid affecting its normal activities. In order to be able to adapt to the extreme temperature difference (-40 °C to + 50 °C) and strong ultraviolet environment of the Qinghai-Tibet Plateau. The shell of the equipment is made of high-strength lightweight materials with waterproof, dustproof and low-temperature resistance. The optical detection module needs to carry out temperature compensation design to ensure that the detection accuracy can be maintained under the condition of severe temperature change, and the reliability of the data can be guaranteed. The use of the improved equipment will bring the following benefits to the research : from the perspective of the real-time position and movement route of the Tibetan antelope, the sensor is more integrated than the radio collar, and the position information is more real-time and accurate ; in the study of specific issues related to the food migration of Tibetan antelope, the sensor can regularly obtain the nutritional marker data of female Tibetan antelope, and then judge the food quality of Tibetan antelope, so as to verify the hypothesis. For the daily protection of Tibetan antelope, this device can obtain basic data such as body temperature and blood pressure of Tibetan antelope for a long time, which is helpful to prevent poaching behavior.

5. Conclusion

In this paper, various biosensors with practical application value in the field of wildlife monitoring are systematically reviewed. The specific role and potential of biosensors in wildlife protection are analyzed, and the future technology development trend and application scenarios are summarized and prospected. On this basis, this paper designs a set of wearable physiological parameter monitoring equipment dedicated to Tibetan antelope. The equipment integrates near-infrared spectroscopy analysis technology and specific antibody detection method, which can realize rapid and minimally invasive detection of key physiological indicators in Tibetan antelope. By monitoring

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the two core nutritional markers of fatty acids and trace elements, the food quality and nutritional status of Tibetan antelope can be evaluated in a timely and accurate manner. The above technical achievements are expected to significantly promote the in-depth study of important ecological issues such as food selection, migration behavior and habitat adaptation mechanism of Tibetan antelope, and have broad application prospects and important practical value in the field of wildlife protection and ecological management.

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