

Antarctic expeditions: A Systematic Review of the Physiological, Nutritional, Body Composition and Psychological Responses to Treks across the Continental Ice

Running head: Physiological, Nutritional, and Psychological Responses of the Antarctic expeditions

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Abstract

Background: Antarctic expeditions, although supported by scientific knowledge, face various challenges, with little research conducted to explore the physical demands explorers experience.

Objective: To summarise physiological, psychological, body composition and nutritional changes faced during trek expeditions in the Antarctic's continental portion.

Design: Systematic review

Information sources: We used PubMed, SportDiscus, PsycINFO, Scopus, Cochrane databases, CINAHL, and Medline Ovid to search studies published up to January 2023.

Eligibility criteria: We included original articles or case reports, published in English, and in peer-reviewed journals; involving both sexes; using both quantitative and qualitative approaches; that considered Antarctic continent expedition, as well as solo exploration/group exploration. Animals, in vitro studies, children, overwinter in the research station, tourist/organized visits to Antarctica or the South Pole, not sleeping on the ice, and ultra-endurance events were excluded. The JBI critical appraisal checklist for case studies was used for quality assessment.

Results: A total of 12 studies met the eligibility criteria. The main findings are reversible changes in bone density and mineral content. Despite high-calorie intake (5000kcal/day or more), participants experienced body weight loss and a decrease in appetite-regulating hormones. Motivation and goal orientation, positive interpersonal communication, and support are important skills during polar expeditions. Multidisciplinary research revealed various physiological and cognitive responses, disrupted sleep patterns, and mood changes.

Conclusion: Prolonged hypobaric hypoxia reduces aerobic capacity and increases anaerobic metabolism, while bone density changes are reversible and weight loss occurs despite high-calorie intake. Effective decision-making, teamwork, and personal growth are crucial for Antarctic explorers. Future studies need to investigate strategies on how to improve physiological functions while maintaining homeostasis.

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Key points:

- Changes in bone density, mineral content, and hormones were observed during Antarctic traverses, but they were reversible.
- Significant changes in body composition with a decrease in body mass, fat tissue, and lean tissue weight were observed pre- to post-expedition.
- Communication and teamwork are crucial during polar expeditions.
- Prolonged hypobaric hypoxia led to a decreased aerobic capacity and increased anaerobic metabolism, indicating the body's adaptive responses to oxygen deprivation at high altitudes.

1. Background

Antarctica is the southernmost continent on earth, surrounded by the Southern Ocean, and considered the coldest, highest, driest, and windiest place on planet Earth [1, 2]. It is regarded as a polar desert, with temperatures often falling below -70°C , inhospitable for any permanent human habitation with minimal vegetation [1]. The first discovery of Antarctica was in 1820, during a Russian expedition led by Fabian Gottlieb von Bellingshausen and Mikhail Lazarev. Several British, French, and American expeditions followed, with the first confirmed landing by a Norwegian team in 1895. The Norwegian Roald Amundsen was the first to reach the geographic South Pole in 1911, followed by British Royal Navy Officer Robert Falcon Scott and his team approximately five weeks later. However, on their return to base camp, all five members of the Terra Nova expedition died. These early Antarctic expeditions are sometimes referred to as the 'Heroic Age of Antarctic Explorations', encompassing the early explorations at the end of the 19th century until the end of the Shackleton-Rowett Expedition in 1921-1922 [3]. Early explorers mostly travelled on foot, accompanied by huskies and ponies, with much of the food and equipment transported by the explorers themselves with little knowledge of the physiological demands [1].

Modern Antarctic expeditions (since approximately 1990s) have the advantage of relying on scientific data, technologies such as satellite phones, GPS, lightweight equipment and tents, better thermal clothing, dehydrated foods, and faster progress while travelling on ski, man-haul, or using kites. Nevertheless, despite these advances the physiological and psychological challenges related to the sub-zero ambient temperatures, trekking uphill from sea level to altitude (e.g., 2,300 m above sea level), 24-hour daylight, difficult and varied terrain, remoteness, and large distances to be covered, still make modern days expeditions challenging and potentially deadly [4, 5]. Solo expeditions face additional challenges in having to cope with social isolation and the absence of companionship. Although modern area explorers may have periodic human contact via satellite phones, this is

not comparable to the multisensory experience of physical nearness and social support in times of stress or anxiety [6].

Despite the number of studies reporting on Antarctic expeditions, there is still little research conducted to explore the physical demands explorers experience. The available literature is limited to small cohorts or case studies, with scarcity in examining the impact on women explorers, such as energy balance, endogenous and/or exogenous substrate utilization, body composition and maintaining performance, salivary stress hormones, and markers of mucosal immunity, appetite-regulating hormones leptin and adiponectin, markers indicative of systemic inflammatory responses, women reproductive, adrenal, and metabolic changes [4, 6-11]. Psychological aspects, such as mood states, sleep patterns, and personality traits have also been examined in various Antarctic expeditions [5, 6, 8]. Some of these findings may serve as a model for other hostile environments such as future space expeditions, where astronauts must maintain adequate nutrition, and physiological and psychological functions despite highly stressful, isolated, confined, and dangerous environments [9].

Studies conducted in the Antarctic, mostly case studies/reports, have addressed different subjects/domains, reporting several findings. However, the direction of these findings is not clear, and also a need to understand the possible strategies to be used in these expeditions (instruments and protocols to be used), is of relevance for future studies. Considering the performance and clinical relevance, as well as identifying potential recommendations and/or gaps in science, this systematic review aims to summarise physiological, psychological, body composition and nutritional changes faced during trek expeditions in the Antarctic's continental portion.

2. Methods

2.1 Protocol and Registration

This systematic review was conducted according to the 2020 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [12]. The protocol was registered at the International Prospective Register of Systematic Reviews (PROSPERO - CRD42022382609).

2.2 Database and search strategy

The following seven key databases, relevant to our research question were searched from inception until January 2023: PubMed, SportDiscus, PsycINFO, Scopus, Cochrane databases, CINAHL, and Medline Ovid. Two sets of keywords were used, which were combined by the use of the Boolean operator AND: set 1 included the different terminologies for Antarctica and was combined with the OR operator (“*South Pole**”, “*solo**”,

“crossing*”, “expedition*”, “Antarctic”) AND (“research medical”, “physiological”, “nutrition”, “sleep”, “psychological”), while the set 2 included the different terminologies for exploration and were combined with the OR operator (“solo”, “crossing*”, “expedition*”). The search was conducted and completed in January 2023.

2.3 Study eligibility criteria and study selection criteria

In Table 1, we present the eligibility criteria for studies included in this review. The identification and screening steps were carried out by the lead author (MT) in collaboration with the co-authors of this review (VS, CV). All records retrieved by the search query were imported into the Endnote X7 software (Thompson Reuters, Carlsbad, CA, USA), and duplicates were removed by the lead author (MT). After the exclusion of duplicate studies, the title and abstract were screened. Full texts of potentially eligible studies were evaluated.

Table 1. Eligibility criteria following the PICOS strategy.

PICOS strategy	Inclusion criteria	Exclusion criteria
Population	Human. Both biological sexes.	Animals and in vitro studies. Explorers aged <18 years
Intervention	Trek Antarctic expedition to the South Pole and beyond (e.g., the crossing of Antarctica, attempted/ failed expeditions to the South Pole), considering solo and group exploration.	Overwinter in the research station, tourist/organized visits to Antarctica or the South Pole, not sleeping on the ice. Data reporting running events.
Comparator	Pre- and post-expedition.	
Outcomes	Physiological, nutritional, psychological, and multidisciplinary variables.	
Study design	Original study articles or case reports published in peer-reviewed journals in the English language, adopting both quantitative and qualitative approaches.	All other study designs.

2.4 Data extraction and study quality assessment

Data extraction was performed by three authors (MT, CV, VS), and a cross-check was done for quality control (MT, CV, VS). Data extraction included: (1) first author name and year of publication; (2) type of study; (3) sample characteristics; (4) expedition details; and (5) main findings. The JBI critical appraisal checklist for case reports was used for quality assessment [13]. The qualitative assessment was performed individually by two reviewers (MT, TNG), and discrepancies were resolved by consensus. Due to the absence of a tool specifically developed to assess the quality of studies designed to evaluate the effects of exposure to isolated, confined, and extreme conditions in healthy individuals (such as those inserted in this review), the JBI critical appraisal checklist for case reports was chosen [14]. This checklist comprises eight criteria: Q1, “Were patient’s demographic characteristics clearly described?”; Q2, “Was the patient’s history clearly described and presented as a

timeline?"; Q3, "Was the current clinical condition of the patient on presentation clearly described?"; Q4, "Were diagnostic tests or assessment methods and the results clearly described?"; Q5, "Was the intervention(s) or treatment procedure(s) clearly described?"; Q6, "Was the post-intervention clinical condition clearly described?"; Q7, "Were adverse events (harms) or unanticipated events identified and described?"; Q8, "Does the case report provide takeaway lessons?". Each criterion was scored as being "met= yes" or "not met= no" or "unclear". Each criterion that was scored as "met= yes" scored one point with the maximum attainable score of 8. The results of this assessment were used to assign an a priori quality rating to each study (0-2 points= very low; 3-4 points= low; 5-6 points= moderate; 7-8 points= high quality). Not all questions in the checklist were applicable to the included studies in this review. In Q5 and Q6 we considered the expedition as the "intervention/treatment", and Q7 was considered as "unclear" in all the studies since it was not investigated in any study because did not comprise the studies' aims.

3. Results

3.1 Literature Search

A total of 1905 studies were identified. After excluding duplicates, 1853 studies were screened by their titles and abstracts. This process allowed a further exclusion of 1815 papers, resulting in 38 papers for full-textual assessment, and 12 studies fulfilled the eligibility criteria and were included in this review. The PRISMA flowchart of search and selection strategies is presented in **Figure 1**.

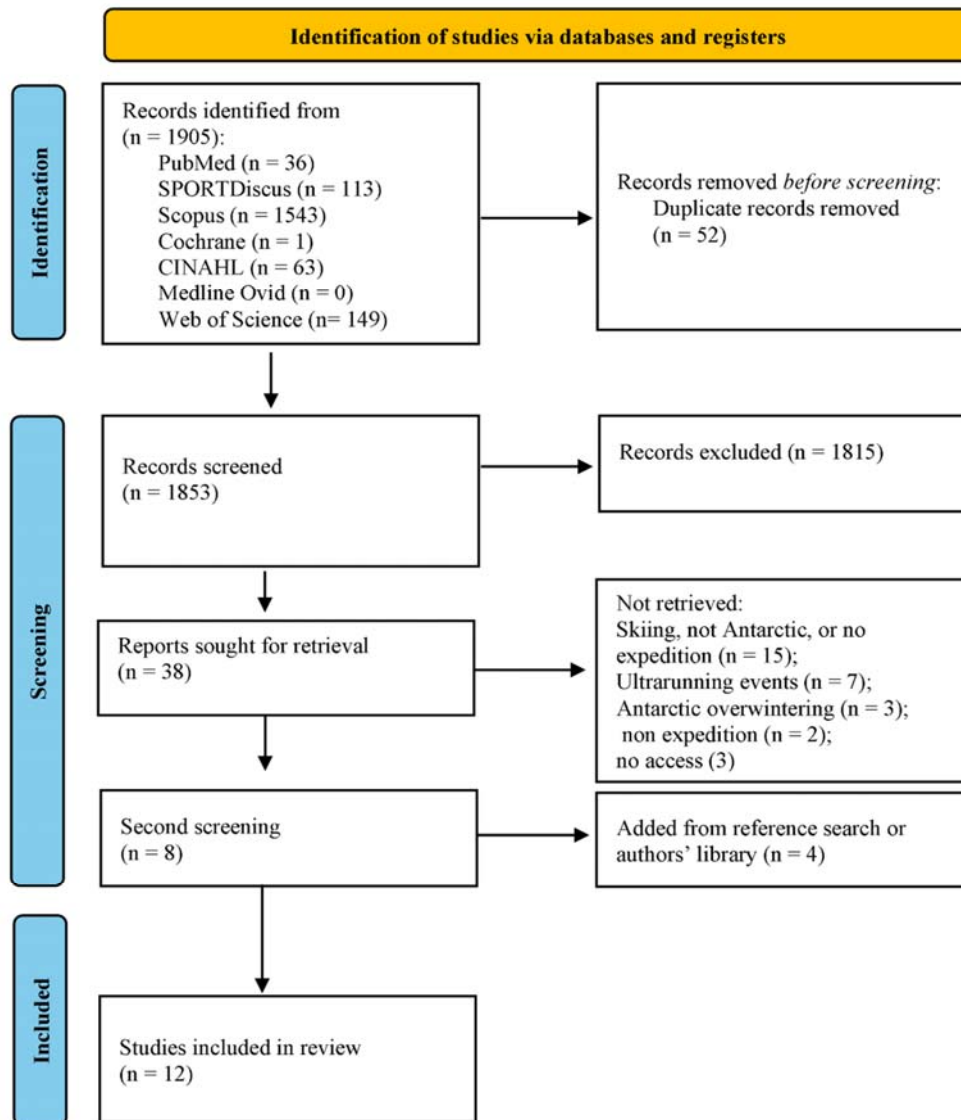


Figure 1. PRISMA flow diagram of the screening process

3.2 Quality assessment

Table 2 presents the results of the quality assessment. Overall, the studies demonstrated a moderate to high level of methodological quality, providing detailed information about the sample, the study design, and the procedures for data collection. However, the studies received a negative rating for Q7, which pertains to the identification and description of adverse events or harms, as this information was not reported. When this information was unclear or missing in the studies, the item was classified as such.

Table 2. Methodological quality assessment results

Author, Year	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Total score
O'Leary et al. [15]	✓	✓	✓	✓	✓	✓	✗	✓	7
Hattersley et al. [16]	✓	✓	✓	✓	✓	✓	✗	✓	7
Hattersley [18]	✓	✓	✓	✓	✓	✓	✗	✓	7
Stroud et al. [17]	✓	✗	✗	✓	✓	✓	✗	✓	5
Anton-Solanas et al. [4]	✓	✓	✗	✓	✓	✓	✗	✓	6
Gifford et al. [10]	✓	✓	✓	✓	✓	✓	✗	✗	6
Gifford et al. [11]	✓	✓	✓	✓	✓	✓	✗	✓	7
Pedlar et al. [5]	✓	✓	✓	✓	⊖	✓	✗	✓	6
Blackadder-Weinstein et al [8]	✓	✓	✓	✓	✓	✓	✗	✓	7
Hattersley [19]	✓	✓	✓	✓	✓	✓	✗	✓	7
Johnsen et al. [9]	✓	✗	✓	✓	✓	✓	✗	✓	6
Atlis et al. [20]	✓	✓	✓	✓	✓	✓	✗	✓	7

Legend: Q1, “Were patient’s demographic characteristics clearly described?”; Q2, “Was the patient’s history clearly described and presented as a timeline?”; Q3, “Was the current clinical condition of the patient on presentation clearly described?”; Q4, “Were diagnostic tests or assessment methods and the results clearly described?”; Q5, “Was the intervention(s) or treatment procedure(s) clearly described?”; Q6, “Was the post-intervention clinical condition clearly described?”; Q7, “Were adverse events (harms) or unanticipated events identified and described?”; Q8, “Does the case report provide takeaway lessons?” [13]; Yes (✓); No (✗); Unclear (⊖). The results of this assessment were used to assign an a priori quality rating to each study (0-2 points= very low; 3-4 points= low; 5-6 points= moderate; 7-8 points= high quality).

3.3 Sample and study characteristics

Based on the heterogeneity of the included studies, four main domains of interest were observed – physiology, nutrition, body composition, and psychology. Given that, studies were grouped, and presented, as follows (according to their results): those focused on physiology (n= 9) [4, 5, 10, 11, 15-19], those focused on nutrition (n= 1) [9], those focused on body composition (n=9) [4, 5, 9, 11, 15-19], and those focused on psychology (n= 6) [4, 5, 8, 10, 11, 20] (Table 3). Most of the studies were designed as case studies [4, 5, 17, 20, 21]. A total of 54 subjects (27 men and 27 women) were examined in the included studies; however, some studies used subjects multiple times and after deleting cases that have been used in more than one study, a total of 42 unique subjects of both biological sexes (21 men and 21 women) were sampled. The expedition details ranged considerably between the studies, including information on the year, environmental conditions, altitude, and duration of the expedition. The first study, published in 1996, assessed the basic biological process of protein turnover and energy balance in two men who crossed Antarctica [17]. The most recent study, published in 2021,

explored nutritional status and levels of appetite-regulating hormones during a solo unsupported crossing of Antarctica [9].

3.4 Instruments/Protocols

Despite the use of different instruments across studies, some similarities were observed. Biomechanical markers were assessed through blood samples [9, 11, 15], urine [16-19], salivary [4, 11], or hair [11] analysis, depending on the specific marker under consideration. Additionally, these analyses were conducted, most of the time, before and after the expeditions [11, 15, 16, 18, 19]. Few studies collected data during the expeditions [4, 9, 17]. Regarding bone mineral density, DXA was the method used [15], which was also used to estimate body composition [4, 11]. Other techniques, such as skinfold measurements [5, 11], underwater weighing [17], plethysmography [16, 18, 19], doubly-labelled water [17], and bioimpedance [11] were also reported for measuring body composition. Calorimetry was the choice to estimate energy expenditure/metabolic rate [16, 18, 19]. Psychological variables were measured, in all studies, via questionnaires [4, 5, 8, 10, 11, 20], but the use of interviews was also included as a strategy to add information from self-reported data [8, 20].

3.5 Studies focused on physiology

One common area of interest is understanding the human body's adaptation to extreme cold, prolonged physical activity, and hypoxic conditions, typical of polar expeditions. In this sense, nine studies investigated physiological and metabolic changes (e.g., total energy expenditure, sleeping metabolic rate, resting metabolic rate, metabolic rate during exercise, and protein turnover rate response) [4, 5, 10, 11, 15-19].

In terms of metabolic response, a research assessed six women in an unsupported traverse of Antarctic. Regarding biomechanical markers of bone turnover, findings showed an increase in bone-specific alkaline phosphatase and phosphate, but a decrease in total 25-hydroxyvitamin D [15]. Additionally, it was observed an increase in parasympathetic dominance, heart rate variability, and a decrease in heart rate and low-frequency:high-frequency (LF:HF) power 15 days post-expedition [10]. Further, the research's findings also showed no changes in basal plasma cortisol, basal sex steroids, corticosteroids, and metabolic markers, fasted glucose, HOMA-B, HOMA-S and HOMA-IR, adjusted calcium, magnesium and phosphate, markers of nutritional status, and follicle-stimulating hormone; but a decrease in leptin and hair cortisol levels [11].

Table 3. Summary of the studies included in the domains of physiology, nutrition, body composition, and psychology domains.

Author, Year	Type of study	Sample characteristics	Expedition details	Variables - instruments	Main findings
Studies focused on Physiology					
O'Leary et al. [15] 2019	Case-series or Exploratory	Six women (32 ± 3 years, body height 1.72 ± 0.07 m, body mass 72.8 ± 4.0 kg)	Each individual hauling 80 kg sledges across 1700 km of the Antarctic during 61 days	- Biochemical markers – venous blood samples	Biochemical markers of bone turnover: ↑ BALP 15 days post-expedition than 4 days post-expedition* ↑ Phosphate was higher 15 days post-expedition than pre-expedition* and 4 days post-expedition* ↔ Sclerostin, P1NP, CTX, magnesium or albumin-adjusted calcium ↓ Total 25(OH)D from pre- to 4 days post-expedition*
Anton-Solanas et al. [4] 2016	Case study	One man (36 years, body height 1.88 m, body mass 94.5 kg).	Hercules station to South Pole (29 days); prior first attempt 7 days but aborted due to bad weather and returning to Hercules Station	- Immunoglobulin A (sIgA), Alpha Amylase (sAA), cortisol (sCort), testosterone (sT) – salivary analysis - Distance covered and hours of physical activity – self-reported	↓ Salivary testosterone ↑ Salivary cortisol increased sAA and sIgA fluctuated ↓ Slowing of reaction time
Gifford et al. [10] 2018	Prospective	Six women (age mean 32.7 years, BMI of 24.9 ± 1.2 kg/m ²)	A total of 1700 km expedition; 61 days, each individual hauling a sled weighing up to 80 kg; temperature range -2 to -40 degrees Celsius	- Heart rate variability – ECG	↑ HF power and RR interval irregularity ↓ Heart rate and LF:HF power at 15 days post-expedition
Gifford et al. [11] 2019	Prospective	Six women (age mean 32.8 years, BMI 24.2 ± 0.97 kg/m ²)	A total of 1700 km expedition; 61 days, each individual hauling a sled weighing up to 80 kg; temperature range -2 to -40 degrees Celsius	- Metabolic and nutritional markers (TSH, fT4, total T3, IGF-1, ferritin, insulin, C-peptide, creatinine, albumin, transferrin, calcium, zinc, iron, phosphate, magnesium, glucose, lactate, leptin, urea, insulin) – blood samples	↔ Basal plasma cortisol ↔ Basal sex steroids, corticosteroids, and metabolic markers ↓ Leptin after the expedition ↔ Fasted glucose, HOMA-B, HOMA-S and HOMA-IR, adjusted calcium, magnesium and phosphate ↔ Markers of nutritional status ↑ Average cortisol levels

				- Reproductive markers (LH, FSH, progesterone, estradiol, SHBG, AMH) – blood samples - Adrenal markers (cortisol, 17OH progesterone, testosterone, DHEA, androstenedione) – blood samples, hair, and saliva	↔ Follicle-stimulating hormone, maintaining the reproductive and hypothalamic-pituitary-adrenal axis function ↑ Hair cortisol
Pedlar et al. [5] 2007	Case study	One woman (43 years, body height 161.3 cm, body mass: 53.5kg, body fat 22.6%)	Solo expedition 600 km to the South Pole within 45 days	- Leg power – counter movement jump - Maximal strength – barbell back squat - VO _{2max} – treadmill test - Sleep and activity – Actiwatch	↓ Loss of body mass
Hattersley et al. [16] 2019	Pre and post	Six men (median age of age 29 years) – but only five completed the traverse	During the 67 days (1750km) of journey, they experienced temperatures as low as -57 C whilst pulling sledges with a planned maximum weight of 120kg to an altitude of 3350m	- Energy expenditure and metabolic rate - calorimetry - Urea and creatinine – urine analysis - Heart rate – movement sensor (Zephyr Biomodule)	Energy expenditure ↓ Lipid utilization in five subjects ↓ Protein utilization in five participants ↑ Carbohydrate utilization in four of the six participants Sleeping Metabolic Rate ↔ Sleeping or resting metabolic rate Resting metabolic rate ↔ RMR Metabolic rate during exercise (EMR-80, EMR-100, and EMR-120) ↑Energy expenditure as the step rate increases ↓Energy expenditure values for step rates of 100 and 120 steps/min (EMR-100 and EMR-120) Heart Rate: ↓ Heart rate on daily average, sleeping, exercising at 100 and 120 steps/min ↔ Diet-induced thermogenesis
Hattersley et al. [18] 2019	Pre and post	Six men (median age of age 29 years) – but only five completed the traverse	During the 67 days (1750km) of journey, they experienced temperatures as low as -57 C whilst pulling sledges with a	- Energy expenditure and metabolic rate - calorimetry - Urea and creatinine – urine analysis	Total energy expenditure: ↓ 8% in total energy expenditure. ↓28 (35) g day ⁻¹ carbohydrate utilization. Sleeping metabolic rate:

			planned maximum weight of 120kg to an altitude of 3350m.		<p>↔ Substrate utilization pre- and post-expedition for the energy expenditure during the two periods of sleep, SMR-1 and SMR</p> <p>Resting metabolic rate:</p> <p>↓ Resting metabolic rate.</p> <p>↔ Average substrate utilization was maintained when the values were normalized to lean tissue weight</p> <p>Metabolic rate during exercise (EMR-80, EMR-100 and EMR-120):</p> <p>↑ Energy expenditure as the step rate increased</p> <p>↓ Energy expenditure at 80 steps min⁻¹</p> <p>↔ Energy expenditure when the values for the 100 step min⁻¹ and 120 step min⁻¹ exercises were normalized to total body mass.</p> <p>↑ Average substrate utilization rates for the three intensities, show a statistically significant increase in carbohydrate utilization</p> <p>↓ Average substrate utilization rates for the three intensities, show a statistically. decreasing in protein utilization for the 80 step min⁻¹ exercise intensity between the pre- and post-expedition values</p> <p>↑ Carbohydrate utilization when the values were normalized to body mass</p> <p>↓ Lipid utilization when the values were normalized to body mass</p> <p>↓ Diet induced thermogenesis</p>
Hattersley et al. [19] 2020	Prospective	Six women (28–36 years) and five men (26–40 years)	<p>Comparison of two expeditions:</p> <p>Men participants: 67 day, 1750 km from the Hercules Inlet to Ross Sea Ice via South Pole. Minimal temperatures – 57 C; pulling sledges weighing up to 120 kg, maximal altitude 3350 m</p> <p>Women participants: 61 days, 1700 km expedition; with everyone hauling a sled weighing</p>	<p>- Energy expenditure and metabolic rate - calorimetry</p> <p>- Urea and creatinine – urine analysis</p>	<p>↔ No difference in resting or sleeping energy expenditure, normalized to lean tissue weight</p> <p>↔ Energy expenditure when exercising at 80, 100 and 120 steps min⁻¹</p> <p>↑ Daily energy expenditure for the men in Spear-17</p>

			up to 80 kg; temperature range -2 to -40 degrees Celsius.		
Stroud and Jackson [17] 1996	Case study	Two men (Men 1: 37 years; Men 2: 48 years)	Two men travelled on foot, hauling sledges for 10-12 h every day. Each sledge had a starting weight of 222 kg and contained 100 days' supplies of food and fuel. Overall, the distance travelled was about 2300 km with a maximum altitude of 3500 m to the highest part of the Antarctic polar plateau	<ul style="list-style-type: none"> - Energy intake – pre-packed diet (weighed and packaged daily ratios) - Energy expenditure – combining energy intake with energy deficits (losses of lean tissues and fat) - Protein turnover (creatinine and urea) – urine analysis 	<p>↓ Energy expenditures.</p> <p>Protein turnover results demonstrated considerable differences in the metabolic responses of the two men to the combined stresses of exercise, cold and undernutrition</p> <p>Both men maintained high and relatively stable levels of protein synthesis during the expedition despite the great exertion and the onset of considerable debilitation</p>
Studies focused on Nutrition					
Johnsen et al. [9] 2021	Longitudinal case study	One man (34 years)	Travelled 4804 km in 93 days	<ul style="list-style-type: none"> - Appetite-regulating hormones (leptin and adiponectin) – dried bloodspot - Nutritional status (albumin, globulin, al/gl-ratio) – dried bloodspot - Immune response (interleukin 6) – dried bloodspot 	<p>↓ Appetite-reducing hormone of leptin and the appetite-stimulating hormone of adiponectin</p> <p>IL-6 levels showed extreme values above normal, except during the recovery phase</p>
Studies focused on Body Composition					
O'Leary et al. [15] 2019	Case-series or Exploratory	Six women (32 ± 3 years, body height 1.72 ± 0.07 m, body mass 72.8 ± 4.0 kg)	Each individual hauling 80 kg sledges across 1700 km of the Antarctic during 61 days	<ul style="list-style-type: none"> - Whole-body areal bone mineral density – DXA - Tibial volumetric bone mineral density, geometry and microarchitecture – HR-pQCT system - Biochemical markers – venous blood samples 	<p>Whole-body areal bone mineral density: ↔ Areal BMD of the arms, legs, pelvis and whole-body ↓ Trunk*, ribs*, and spine* aBMD*</p> <p>Volumetric bone mineral density: ↔ Total, trabecular and cortical vBMD of the tibial metaphysis ↔ Cortical vBMD of the tibial diaphysis was not significantly different between pre- and post-expedition Geometry:</p>

					↔ Trabecular bone volume, trabecular area, cortical area cortical thickness and cortical perimeter, data not shown) of the tibial metaphysis ↔ Trabecular area, cortical area, cortical thickness, and cortical perimeter of the tibial diaphysis Microarchitecture: ↔ Trabecular number, trabecular thickness, trabecular spacing, cortical pore diameter, and cortical porosity for the tibial metaphysis ↔ Cortical pore diameter and cortical porosity for the tibial diaphysis Mechanical strength: ↔ Stiffness and failure load for the tibial metaphysis, and stiffness and failure load for the tibial diaphysis
Anton-Solanas et al. [4] 2016	Case study	One man (36 years, body height 1.88 m, body mass 94.5 kg)	Hercules station to South Pole (29 days); prior first attempt 7 days but aborted due to bad weather and returning to Hercules Station	- Body composition and bone mineral density – DXA	↓ Body mass and sum of 8 skinfolds ↓ Girth circumferences ↓ Fat percentage and fat mass ↑ Total lean mass ↓ Lean mass in the arms and legs ↑ Lean mass in the trunk area
Gifford et al. [11] 2019	Prospective	Six women (age mean 32.8 years, BMI 24.2 ± 0.97 kg/m ²)	A total of 1700 km expedition; 61 days, each individual hauling a sled weighing up to 80 kg; temperature range -2 to -40 degrees Celsius	- Body composition – DXA, skinfolds, bioimpedance	↓ Body mass.
Pedlar et al. [5] 2007	Case study	One woman (43 years, body height 161.3 cm, body mass: 53.5kg, body fat 22.6%)	Solo expedition 600 km to the South Pole within 45 days	- Body fat – skinfolds	↓ Loss of body mass
Hattersley et al. [16] 2019	Pre and post	Six men (median age of age 29 years) – but only five completed the traverse	During the 67 days (1750km) of journey, they experienced temperatures as low as -57 C whilst pulling sledges with a planned maximum weight of 120kg to an altitude of 3350m	- Body composition – plethysmography (BodPod)	↓ Body weight and fat weight (p<0.05)

Hattersley et al. [18] 2019	Pre and post	Six men (median age of age 29 years) – but only five completed the traverse	During the 67 days (1750km) of journey, they experienced temperatures as low as -57 C whilst pulling sledges with a planned maximum weight of 120kg to an altitude of 3350m	- Body composition – plethysmography (BodPod)	↓ 53% in fat tissue* ↓ Average lean tissue weight. ↓ 7% in body mass*
Stroud and Jackson [17] 1996	Case study	Two men (Men 1: 37 years; Men 2: 48 years)	Two men travelled on foot, hauling sledges for 10-12 h every day. Each sledge had a starting weight of 222 kg and contained 100 days' supplies of food and fuel. Overall, the distance travelled was about 2300 km with a maximum altitude of 3500 m to the highest part of the Antarctic polar plateau	- Body composition – doubly-labelled water (isotopes ¹⁸ O and ² H) and underwater weighing (He-dilution spirometer)	↓ Body mass
Hattersley et al. [19] 2020	Prospective	Six women (28–36 years) and five men (26–40 years)	Comparison of two expeditions: Men participants: 67 day, 1750 km from the Hercules Inlet to Ross Sea Ice via South Pole. Minimal temperatures – 57 C; pulling sledges weighing up to 120 kg, maximal altitude 3350 m. Women participants: 61 days, 1700 km expedition; with everyone hauling a sled weighing up to 80 kg; temperature range -2 to -40 degrees Celsius	- Body composition – plethysmography (BodPod)	↑ Lean tissue weight for Spear-17 participants ↓ Lean tissue weight by Ice Maiden participants
Johnsen et al. [9] 2021	Longitudinal case study	One man (34 years)	Travelled 4804 km in 93 days	- Body weight	↓ Body mass

Studies focused on Psychology

Atlis et al. [20] 2004	Case study	Two women (woman 1: 45 years, body fat 23.4%; Woman 2: 47 years, body fat 19.9%).	The trek covered ≈2,861.41 km (1778 miles); daily distances ranged between 0 to ≈124.72 km (77.5 miles)/day, depending on wind conditions and terrain. Temperatures ranged from ≈ -10°C to -31°C (+14 to -31°F); the altitude range was from sea level to ≈3337.56 m (10950 ft). They pulled sleds that weighed ≈ 113.4 kg (250 lbs) when full	- Personality – Multidimensional Personality Questionnaires (MPQ) and Personality Characteristics Inventory (PCI) - Coping – Utrecht List (UCL) - mood, significant events, coping, physical status, attitudes and expectancies about the trek, dyadic processes, and perceptions and reactions to various environmental factors – weekly form - Stress, coping, and personal experiences; work experiences; privacy, sleep, environment, and health experiences; personal/interpersonal; logistic issues - interview	Both showed a desire to work hard High achievement motivation and goal orientation. Solid leadership and problem-solving skills Ability for positive interpersonal communication and support despite stressful conditions
Anton-Solanas et al. [4] 2016	Case study	One man (36 years, body height 1.88 m, body mass 94.5 kg).	Hercules station to South Pole (29 days); prior first attempt 7 days but aborted due to bad weather and returning to Hercules Station.	- Subjective data (sleep quality and duration, energy levels, perceived exertion, mood, muscle soreness and muscle/joint pain) – 10-point Likert scale - Cognitive function – Axon Sports Cognitive Priming Application (ASCPA)	↔ Subjective ratings of energy level. ↑ Subjective ratings of muscle soreness and muscle/joint pain
Gifford et al. [10] 2018	Prospective	Six women (age mean 32.7 years, BMI of 24.9 ± 1.2 kg/m ²)	A total of 1700 km ski expedition; 61 days, each individual hauling a sled weighing up to 80 kg; temperature range -2 to -40 degrees Celsius	- Anxiety – Beck Anxiety Inventory (BAI)	↔ anxiety scores
Gifford et al. [11] 2019	Prospective	Six women (age mean 32.8 years, BMI 24.2 ± 0.97 kg/m ²).	A total of 1700 km expedition; 61 days, each individual hauling a sled weighing up to 80 kg; temperature range -2 to -40 degrees Celsius	- Psychosocial stress - Impact of Events Scale-Revised (IES-R) - Depressive symptoms – Patient Health Questionnaire (PHQ-9) - Anxiety – Beck Anxiety Inventory (BAI)	↓ Psychosocial stress and financial stress, and fewer significant adverse events post-expedition ↑ Markers of disordered eating risk

				<ul style="list-style-type: none"> - Resilience - Connor Davidson Resilience Scale 10 (CDRISC 10) - Eating disorder – Brief Eating Disorders in Athletes Questionnaire (BEDA-Q) - Perceived exertion, psychological stress, restfulness of sleep, confidence the team - 10-point Likert scale 	
Pedlar et al. [5] 2007	Case study	One woman (43 years, body height 161.3 cm, body mass: 53.5kg, body fat 22.6%)	Solo expedition 600 km to the South Pole within 45 days	<ul style="list-style-type: none"> - Sleep and activity – Actiwatch - Mood – Brunel Mood Scale (BRUMS) 	<ul style="list-style-type: none"> ↓ Hours spent asleep throughout the expedition ↓ Vigor ↑ Increase in fatigue
Blackadder-Weinstein et al. [8] 2019	Prospective	Six women (age range of 28–36 years).	Trek across Antarctica to Hercules Inlet covering 1700 km in 61 days, pulling sledges with all their gear. Skiing for 10 h/d, each team member leading a 75-min leg, with an 8-min rest stop in between, followed by two 45-min legs at the end of the day. The team reached the South Pole in 26 days covering 577 km. Skiing between 12 to 40 km/d, up to 46 km/d in the last portion of the trek. The temperature ranged from –14°C to –56°C	<ul style="list-style-type: none"> - Personality – Multidimensional Personality Questionnaire Brief Form (MPQ-BF) - Psychopathy – Triarchic Psychopathy Measure (TriPM) - Perceived importance of values – Portrait Values Questionnaire (PVQ) - Positive and negative affect and events, environmental and physical factors, coping, strategy/team decision, significant events – Weekly Rating Form - Team interactions, group processes, post-expedition expectations, applications for space missions - interview 	The team was high on personality traits of Achievement, Social Closeness, and Absorption and Positive Emotionality The group self-identified with the following values: Hedonism, Stimulation, and Self-Direction The post-expedition value hierarchy was consistent: Stimulation, Hedonism, and Self-Direction were the three highest self-identified values Significant differences on the PVQ were found on the Tradition and conformity scales comparing pre- and post-expedition

Legend: *p<0.05; DXA, dual-energy x-ray absorptiometry; BM, body mass; BMI, Body Mass Index; km, kilometer; BMD, bone mineral density); vBMD, volumetric BMD; PINP, amino-terminal propeptide of procollagen Type 1; BALP, bone-specific alkaline phosphatase; CTX, c-telopeptide cross-links of type 1 collagen; 25(OH)D, 25-hydroxyvitamin D; RMR, resting metabolic rate; EMR, exercise metabolic rate; EMR-80, energy expenditure values for step rates of 80 steps/min; EMR-100, energy expenditure values for step rates of 100 steps/min; EMR-120, energy expenditure values for step rates of 120 steps/min; SMR-1, first sleep period; SMR, sleeping metabolic rate; SpO2, peripheral capillary oxygen saturation); sIgA, secretory immunoglobulin A); sAA, salivary alpha amylase; sCort, salivary cortisol; sT, salivary testosterone; ASCPA,

Axon Sports Cognitive Priming Application; aBMD, areal bone mineral density; VO₂, pulmonary oxygen uptake; IL-6, interleukin-6; HF, high-frequency; LF, low-frequency; HOMA, homeostatic modeling assessment; HOMA-B, homeostatic modeling assessment for beta cell function; HOMA-S, homeostatic modeling assessment insulin sensitivity; HOMA-IR, homeostatic modeling assessment insulin resistance; PVC, Personal Values Questionnaire; al/gI-ratio, albumin/globulin ratio; ¹⁸O, isotope of oxygen; ²H, isotope of hydrogen; He, helium; lbs, pound; ft, feet; ECG, electrocardiogram; MPQ, Multidimensional Personality Questionnaires; PCI, Personality Characteristics Inventory (PCI); UCL, Utrecht Coping List; BAI, Beck Anxiety Inventory; IES, Impact of Events Scale-Revised; PHQ-9, Patient Health Questionnaire; CDRISC-10, Connor Davidson Resilience Scale 10; BEDA-Q, Brief Eating Disorders in Athletes Questionnaire; BRUMS, Brunel Mood Scale; MPQ-BF, Multidimensional Personality Questionnaire Brief Form; TriPM, Psychopathy – Triarchic Psychopathy Measure; PVQ, Portrait Values Questionnaire; TSH, thyroid-stimulating hormone; fT₄, free thyroxine; T₃, triiodothyronine; IGF-1, insulin-like growth factor-1; LH, luteinizing hormone; FSH, folliclestimulating hormone; SHBG, ex hormone-binding globulin; AMH, anti-müllerian hormone; DHEA, dihydroepiandrosterone

Anton-Solanas et al. [4] reported physiological adaptations to the extreme environment such as changes in heart rate and cortisol levels. An increase in aerobic capacity and decrease in leg power were found in the study conducted by Pedlar et al. [5]. Two other studies showed changes in metabolic rate and the proportion of substrate utilization in men [16, 18], and results suggested that the body can adapt to prolonged physical activity in response to exposure to extreme environments [19]. Another study focused on protein turnover rates, which were higher during the early stages of the expedition, but decreased as the body adapted to prolonged physical activity and cold exposure [17].

3.6 Studies focused on nutrition

One study was conducted to investigate the nutritional and metabolic aspects [9], and results revealed the effects of appetite-regulating hormones and indicators of nutrition status. Moreover, despite higher calorie intake, a considerable decrease in body weight and body fat percentage was observed during the expedition, highlighting the challenges of meeting nutritional requirements during strenuous polar expeditions.

3.7 Studies focused on body composition

Changes in body composition, such as bone mineral density, body mass, and body fat, were investigated in the majority of the studies [4, 5, 9, 11, 15-19]. O'Leary et al [15] examined the skeletal response of a women unassisted Antarctic traverse, focusing on bone density and mineral content. The study found that while bone density and mineral content decreased during the traverse, they returned to normal levels 15 days after the expedition. Body mass [4, 5, 9, 11, 16-18] and body fat [4, 16, 18] showed similar patterns across the studies, with a reduction after the traverse. However, different results were observed for lean tissues, with studies showing a reduction [16, 18], an increase [4], and also differences according to sex [19] – increase among men, but a reduction among women.

3.8 Studies focused on psychology

Six studies assessed psychological attributes. Anton-Solanas et al. [4] assessed the physiological and cognitive responses to an Antarctic expedition and found that the participant experienced changes in cognitive function and sleep patterns. Similarly, Pedlar et al. [5] found significant disruptions in sleep and mood that could have negative effects on overall health and well-being. Gifford et al. [10] did not find changes in anxiety among the women travellers. However, it was observed low levels of psychosocial and financial stress, and few

significant adverse events, before the expedition, and an increase in markers of disordered eating risk after the intervention [11].

Regarding teamwork, Blackadder-Weinstein et al. [8] examined individual attributes, values, and goals of a group of military women participating in an Antarctic expedition and found that the women shared common values and goals related to teamwork, leadership, and personal growth, which contributed to the expedition's success. While Atlis et al. [20] focused on the decision-making process and interaction between men and women during expedition, and their findings indicated that women explorers were able to make decisions collaboratively and effectively, with each team member bringing unique skills and perspectives to the expedition. The study emphasized the importance of communication and teamwork during polar expeditions.

4. Discussion

Our purpose was to review medical research findings of modern Antarctic explorations. We provide a synthesis of current research findings, highlight research gaps, and provide direction for future research. A total of 12 studies met the eligibility criteria, with most studies designed as case studies, comprising a total of 42 unique subjects (21 women; 21 men). Studies were published between 1996 and 2021, demonstrating a recent research interest in this topic (Figure 2).

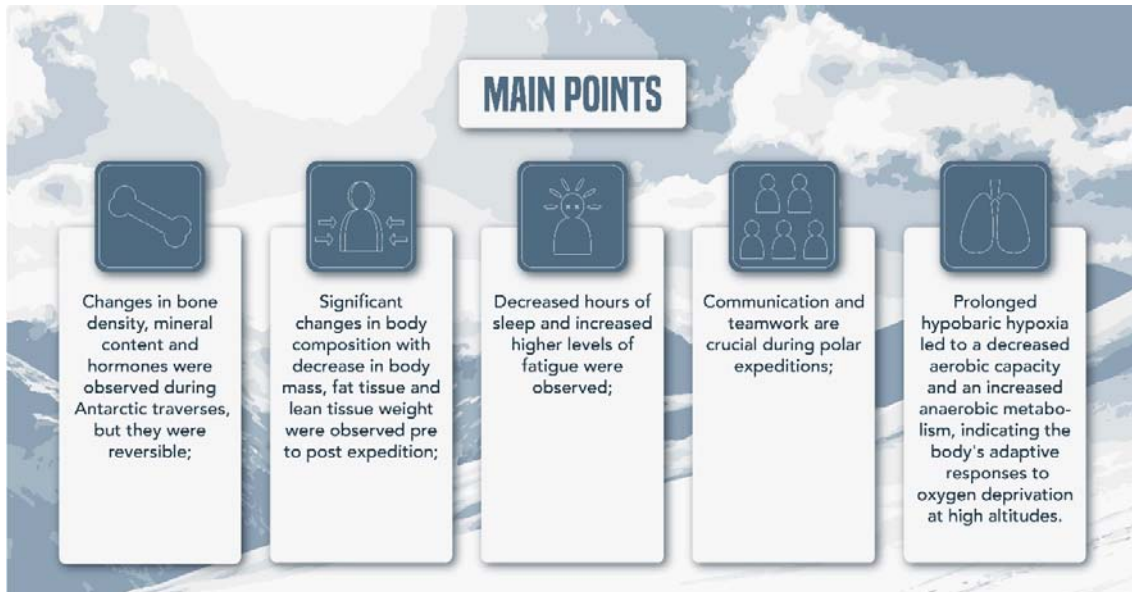


Figure 2. Main findings

The first point to address concerns the instruments and protocols used for data collection. Due to environmental constraints, most data collection occurred before and after the expedition, as it involved high-cost

equipment that is difficult to transport and manage in the field (e.g., DXA, BodPod, bioimpedance), and required a laboratory setting for data collection and/or storage (e.g., doubly-labelled water, urine and blood samples). Dried bloodspot, on the other hand, enables data collection during the expedition, allowing the tracking of changes in biomarkers. Although this method requires training travellers in data collection and storage procedures, it is a viable alternative to laboratory methods. Furthermore, assessing psychological variables through questionnaires offers an easy and practical approach that can be used at various points across the journey.

Understanding human physiological responses under extreme environmental conditions is of interest to many researchers. In Antarctic expeditions, the traversers are exposed to lower temperatures, higher altitudes, and sunlight deprivation. At high altitudes, the lower level of oxygen in the air results in reduced blood oxygenation [22], which presents with important metabolic and hormonal changes throughout the expedition. For example, Gifford et al. [10] found a decrease in heart rate variability during a 61-day unassisted Antarctic traverse. Considering that the heart rate variability is an indicator of the autonomic nervous system's function, the decrease in this index suggests that the participant's autonomic nervous system was temporarily impacted by endurance activity. These results suggest that recovery time should be taken into account during these expeditions.

Investigating the skeletal responses of six women in an unassisted Antarctic traverse, O'Leary et al. [15] showed that bone density and mineral content decreased during the traverse but returned to normal levels after the expedition. These results are similar to a study that included 120 healthy adults, who spent a year in Antarctica [23]. The authors reported that prolonged sunlight deprivation (even during summers, since freezing temperatures demand protective clothing, and high solar UVB radiation exposure demands the use of sunscreen, which limits sunlight exposure [24-26]) resulted in significant reductions in bone density and mineral content. However, these changes were reversible, as bone density and mineral content returned to normal levels following exposure to sunlight. These results are related to the effects of prolonged energy deficit, which highlights the relevance of an accurate nutritional balance during the traverse, including supplementation strategies. Similarly, the effect of prolonged exposure to extreme cold on the immune systems should be deeper explored to find strategies to better protect explorers' health. Bone density and mineral content are relevant aspects considered during spatial journeys. Therefore, results derived from Antarctic expeditions may provide insights to help spatial scientists in the future.

Another study focused on protein turnover rates, which were higher during the early stages of the expedition but decreased as the body adapted to prolonged physical activity and cold exposure [17]. Understanding the protein turnover rates is important for several factors, including the comprehension of

nutritional and physical demands, health, and muscular recovery, as well as protein synthesis under extreme conditions. Acute exposure to hypoxia may trigger immediate physiological responses, such as an increase in heart rate and ventilation, to maintain oxygen supply to vital organs [27]. These acute responses aim to enhance oxygen delivery and maintain energy production through aerobic pathways. However, with prolonged or chronic exposure to hypoxia, the body undergoes adaptive changes that can lead to a decrease in aerobic capacity and an increase in anaerobic metabolism.

In addition, hypoxia also alters the energy metabolism [27], which is associated with the exposition to higher altitudes and cold temperatures. Studies assessing metabolic rate showed differences between both sexes. For example, a study investigating metabolic rate in men found that, at low levels of exertion, while it increased during the expedition, substrate utilization remained constant. But for other physiological states no statistically significant differences were found, suggesting that the body can adapt to prolonged physical activity in cold environments [16]. Among six women in an unsupported traverse of the Antarctic, a decrease in body composition (i.e., fat weight, lean tissue weight, and body weight) and exercise energy expenditure (at 100 and 120 steps/min intensities) were shown [18]. Similar results, for women, were reported by Gifford [11] regarding body composition (body mass and fat mass) with no substantial changes in markers of reproductive function, and an increase in hair cortisol during the expedition. These findings provides information about how extreme environmental conditions can affect woman's body. It can be used for planning and supporting individuals undertaking such expeditions.

Regarding the nutritional aspects of polar expeditions, the overall findings suggest several challenges to maintaining adequate nutrition and hydration in extreme environments, since that significant weight loss occurred [9]. Significant differences were also found between the sexes [19]. A study examining 17 athletes covering 800 km to the South Pole during an adventure race showed significant negative changes in energy balance which partly explained reduced body mass [28]. Differences were also found between the sexes, highlighting the need for individualized planning and a strategic approach for polar expeditions, emphasizing the importance of tailored plans for individuals based on their specific needs and preferences [4, 5]. A previous study showed that energy intake varied between a mean daily amount of $\sim 6,500 \text{ kcal/day}^{-1}$ for men athletes traversing Antarctica and $\sim 5,000 \text{ kcal/day}^{-1}$ for women athletes [29]. During the journey, the athletes experienced temperatures as low as $-57 \text{ }^\circ\text{C}$ whilst pulling sleds weighing up to 120 kg for men and up to 80 kg for women. The higher daily energy expenditures for men were thought to be due to higher physical demands resulting in reduced demand for energy to thermoregulate compared to women. Another study showed that men and women may have similar energy

expenditure and substrate utilization when exposed to the same extreme environments [29]. Few studies examined salivary hormones and markers of mucosal immunity during expedition [4] as well as appetite-regulating hormones leptin and adiponectin and inflammatory markers such as Interleukin-6 (IL-6), demonstrating a marked reduction in levels of the appetite-reducing and stimulating hormones, as well as a substantial increase in IL-6 levels [9].

The psychological aspect, mood states, and personality traits have also been examined in various Antarctic expeditions [5, 6] as well as sleep patterns. During a 44-day solo expedition to the South Pole, average sleep times were around 5 hours per day which decreased to an average of 3 hours per day during the final stages of the expedition. Interestingly, the athlete was able to sustain the high workload despite decreases in sleep times [5]. Some of these findings may serve as a model for other hostile environments such as future deep space expeditions, where astronauts must maintain adequate nutrition, and physiological and psychological functions despite highly stressful, isolated, confined, and dangerous environments [9].

4.1 Limitations and future recommendations

The findings of this review need to be considered in the context of the limitations, including the search of studies only in English. In terms of methodological aspects, most of the studies are observational research, which may be subject to confounding factors and cannot establish causal relationships between the variables studied. Further, the use of the JBI critical appraisal checklist for case studies reports for quality assessment has limitations since the checklist was developed for the context of clinical decision-making in healthcare; however, the absence of a checklist that fits in the present study led us to decide about its use. We were aware of the limitations related to this decision, and some adaptations were performed, to maximize the quality of the evaluation of the process of the studies. Additionally, the included studies cover a wide range of topics, but the sample sizes and specific methodologies may vary, which could affect the generalizability and reliability of the findings, as well as the importance of considering individuality when expeditions are planned. Therefore, further research is needed to provide a comprehensive understanding of the physiological responses and optimal strategies for nutrition, physical activity, and overall well-being during Antarctic expeditions.

Notably, none of the studies have provided information regarding adverse or unanticipated events during the expedition. Although this is a significant achievement, it is important to acknowledge that Antarctic expeditions can be dangerous and potentially fatal. Even with all the precautions and support, the inherent risks remain substantial. This underscores the need for meticulous planning and caution in the development and

execution of research in this context, which may also explain the limited number of studies available in this area/environment. On the other hand, the absence of a description of adverse events does not imply that none occurred, and it may reflect a lack of authors' interest in documenting these incidents. This information should be interpreted with caution, and future studies should ensure that any adverse events, if observed, are carefully reported.

Antarctic expeditions are challenging, not only due to the environmental constraints but also regarding the logistical demands. Research in this context requires significant time, high-cost equipment, a multi-professional research team, and well-trained participants (travelers) to face the challenge. This systematic review provides a robust summary of the available studies related to physiological, nutritional, body composition, and psychological responses during the South Pole traverse. It highlights existing research gaps, and also presents feasible methods and instruments for measuring, for example, biochemical markers, as well as protocols for food supply control and necessary equipment. Researchers can use this information to delineate future studies, with protocols that include travellers for both sexes (allowing sex-differences comparisons), and data collection over multiple years (enabling tracking changes over time), which will improve the strategies to better support travelers throughout their journey, and also the application of the findings to other areas, such as space expeditions.

These findings contribute to our understanding of how the human body responds to extreme environments and may have implications for the planning and execution of future Antarctic expeditions, protecting the health and well-being of the expeditioners. For example, despite the considerable energy intake, most studies showed significant weight loss during the expedition. Future studies should consider investigating whether different nutritional and supplement strategies can be adopted to avoid negative consequences on weight loss or, on the other hand, to investigate whether this outcome is expected in this type of journey expedition, regardless of the supplementation used. In addition, investigations into the impact of low temperatures on basal metabolic rate and core temperature maintenance should be considered to optimize the nutritional security. Further research is needed to examine the effects of extreme environments on appetite-regulating hormones, inflammatory markers, and markers of mucosal immunity to gain a comprehensive understanding of their impact on overall health.

5. Conclusion

The studies conducted on Antarctic expeditions provide insight into various aspects of physiology, nutrition, psychology, and multidisciplinary factors. Regarding physiology, the investigations revealed that prolonged hypobaric hypoxia led to decreased aerobic capacity and increased anaerobic metabolism, indicating

the body's adaptive responses to oxygen deprivation at high altitudes. Additionally, changes in bone density and mineral content were observed during Antarctic traverses, but they were reversible. Despite higher calorie intake, weight loss and decreases in appetite-regulating hormones were observed. In terms of psychology, the studies highlighted the importance of effective decision-making, teamwork, and personal growth during polar expeditions. Finally, the multidisciplinary studies demonstrated a range of physiological and cognitive responses, disrupted sleep patterns, and changes in mood and psychological state among expedition participants. These results can guide future research and help optimize the planning and execution of Antarctic expeditions, ensuring the well-being and health of explorers in extreme environmental conditions.

Declarations

Author contributions: Planning: Mabliny Thuany, Carel Viljoen and Volker Scheer; Research conduction: Mabliny Thuany, Carel Viljoen, Thayse Natacha Gomes, and Volker Scheer; Original draft: Mabliny Thuany, Carel Viljoen, Volker Scheer; Edit and critical review: Mabliny Thuany, Carel Viljoen, Thayse Natacha Gomes, Encarna Valero, Beat Knechtle, Ricardo Costa, Mathias Steinach, and Volker Scheer. All authors read and approved the final version.

Ethics Approval and Consent to Participate

Not applicable.

Consent for publication

Not applicable.

Availability of Data and Materials

Not applicable.

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