Review Article

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Anaesthesia Section

Anaesthetic and Resuscitation Challenges in Austere, Remote or Hyperbaric Environments: A Narrative Review

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ABSTRACT

Resuscitation and anaesthesia in austere, remote and hyperbaric environments present unique challenges due to extreme physiological stresses, limited resources and environmental limitations. High-altitude, deep-sea, hyperbaric and space-analogue environments each introduce unique physiological responses that alter oxygen availability, pressure shifts and fluid displacement. These changes significantly affect pharmacokinetics, haemodynamics and patient stability, adding complexity to care. Physiological responses such as altered gas exchange and changes in circulatory dynamics require careful monitoring and management. The lack of adequate hardware and monitoring equipment often forces clinicians to adapt with creative workarounds or rely on transportable technology. Limited diagnostic tools and the inability to constantly monitor vital signs pose additional risks, requiring adaptability and resourcefulness. Resource, staff and isolation constraints complicate airway management, ventilation, fluid resuscitation and emergency procedures. Clinicians must often make quick, high-stakes decisions without immediate backup or access to advanced equipment. Given these constraints, simulation training, telemedicine support and rapid decision-making drills are crucial for enhancing clinicians' preparedness to perform under pressure. Pharmacologic adaptation, monitoring modifications and development of customised anaesthetic and resuscitation protocols are essential to mitigate risks. Anaesthetic agents and fluid resuscitation strategies must be carefully tailored to ensure stability in environments with altered pressures or oxygen levels. The present review analyses the physiological effects and limitations of anaesthesia and resuscitation in extreme conditions, focusing on all phases of care, from initial resuscitation to postoperative recovery. The strategies discussed provide critical insight into how to optimise care and enhance patient safety under extreme conditions.

Keywords: Acclimatisation, Gravity, Pharmacokinetics, Telemedicine, Ventilation

INTRODUCTION

The safe and effective administration of anaesthetics and resuscitation in austere, remote, or hyperbaric settings is a demanding challenge for clinicians. Traditional standards of care depend upon strong infrastructure, abundant equipment, trained staff and convenient access to tertiary services. In contrast, settings like high-altitude outposts, space analogues, or submersible habitats impose drastic limitations, including confined resources, communication delays, altered physiology and risks to the host environment. These constraints add to the dangers of anaesthesia and resuscitative care and necessitate a rethink of standard practice. Survival in such environments requires flexibility, equipment, alternative protocols and interdisciplinary knowledge of physiology, engineering and emergency medicine [1].

Environmental stressors, such as hypoxia, pressure extremes and altered gas dynamics, undermine human physiology in complex ways, affecting pharmacokinetics, cardiovascular response and gas exchange across the lungs. Logistics impose restrictions on monitoring, ventilation support, fluid and blood product availability and standby backup. Resuscitation attempts for airway, haemorrhagic shock, or cardiac arrest have to deal with delays, primitive equipment and insufficient rapid evacuation. The evolving interaction of hostile environment, reduced support and derangement of physiology keeps these interventions on the border of being possible [1,2].

The present review integrates existing knowledge regarding the specific challenges to anaesthetic and resuscitation management in remote, austere, or hyperbaric environments, emphasising where body stressors and environmental limitations interact to alter standard practice. It summarises existing practices and new technological developments and identifies areas with gaps in evidence and capacity.

DISCUSSION

Features of Remote, Austere and Hyperbaric Environments

Remote, austere and hyperbaric environments share several common characteristics that present enormous obstacles to medical practice and survival. They are commonly remotely situated, have minimal infrastructure and are far from trained staff, facilities and evacuation devices. The environment is highly demanding, with variations in temperature, humidity, air pressure and gas composition. Alternative sources of power and operational communications are unavailable or unreliable. In most situations, medical staff must operate with limited or improvised equipment, working under conditions that restrict monitoring, sterilisation and resuscitation capabilities. Physical hazards arise from exposure, entrapment, immersion, or mechanical trauma, among others. Furthermore, environmental stressors such as cold, heat, radiation and dehydration complicate human performance and recovery [3,4].

Hyperbaric conditions impose extra physical and physiological loads related to higher ambient pressure, compression and decompression stress. Increased partial pressures of oxygen, loading with nitrogen and gas kinetics may cause oxygen toxicity, decompression sickness, or barotrauma of the lung, sinuses and central nervous system. Equipment must operate under pressure, form seal-tight connections and refrain from ignition or contamination in high-oxygen atmospheres. High altitude presents the reverse condition of hypobaric hypoxia, accompanied by added cold, dryness and severe ultraviolet radiation. The capacity for body acclimatisation is restricted and steep ascent or long-term exposure results in derangement of oxygenation, fluid imbalance and altered ventilatory control. Added complexity involves space-analogous and deep-sea environments, which impose the effects of changed gravity, confinement and severe remoteness. These conditions compromise cardiovascular and musculoskeletal regulation; alter drug distribution; and add psychological burden by degrading mobility, producing sensory deprivation and increasing confinement [5-7].

Physiological Consequences of Extremes

Extreme conditions impose modified external states on the human body, resulting in severe internal physiological alterations. The impact is most general on the breathing apparatus. In high-altitude or hypobaric states, a reduced partial pressure of oxygen is observed due to a decrease in barometric pressure, resulting in smaller quantities of oxygen entering the blood. Hyperpnoea, augmented ventilation and peripheral chemoreceptor stimulation are attempted reactions to this reduction of oxygen saturation. It tends to increase breathing depth and rate in opposition to it. Over time, the kidneys establish an acid-base balance through bicarbonate excretion, which helps reverse respiratory alkalosis. The cardiovascular system is also under tremendous stress. During hypoxia or hyperbaric stress, the sympathetic nervous system is activated, resulting in increased heart rate and cardiac output that attempt to maintain tissue perfusion and oxygen delivery. Pulmonary vasoconstriction in hypoxic lung areas increases pulmonary arterial pressure and can lead to right ventricular stress. Movement of fluid can be detected; in most cases, this results in diuresis, decreased plasma volume and elevated haematocrit. All these effects enhance the oxygen-carrying capacity, but also increase blood viscosity, leading to an increased workload for the heart [2,8-10].

At the cellular and metabolic levels, hypoxia results in low oxygen levels, leading to the activation of hypoxia-inducible factors, increased anaerobic metabolism, increased lactate production and alterations in the activity of enzymes that regulate oxidative phosphorylation. At hyperbaric pressures, elevated partial pressures of oxygen may cause oxidative stress, the production of reactive oxygen species and potential toxicity to the lung parenchyma, central nervous system organs and other sensitive organs that are particularly susceptible to oxygen. Altered ambient pressure also affects gaseous kinetics. As ambient pressure increases with depth, so does the dissolution of inert gases in tissues, increasing the risk of gas narcosis and susceptibility to decompression sickness during ascent. Compression stresses include air-filled cavities within the body, such as the middle ear, sinuses and lungs. Renal excretory function is impaired in the presence of acid-base imbalance and dehydration. Hypoxia or pressure changes, along with decreased quality sleep and impaired thinking, disrupt sleep. The musculoskeletal system exhibits effects such as decreased muscle mass, mitochondrial concentration and preserved endurance in the long term. Thermoregulation is disrupted by cold, heat, or fast environmental change [8,11-13]. A comparative overview of the physiological effects across high-altitude, hyperbaric and space environments is provided in [Table/Fig-1] [1,5,8,10,13-16].

Factor	High altitude [13-15]	Hyperbaric [1,5]	Space (microgravity/low gravity) [8,10,16]
Oxygen availability	Reduced partial pressure of oxygen due to lower barometric pressure	Elevated partial pressure of oxygen	Reduced partial pressure of oxygen in microgravity environments
Breathing response	Hyperpnoea (increased breathing depth and rate)	Hyperventilation (due to high oxygen levels)	Altered respiratory pattern due to fluid shifts in the lungs
Kidney Response	Acid-base balance through bicarbonate excretion	Decreased renal excretion with fluid retention	Impaired renal excretory function, fluid shifts
Cardiovascular response	Increased heart rate and cardiac output; pulmonary vasoconstriction increases pulmonary arterial pressure	Increased cardiac workload due to oxygen toxicity risk	Cardiovascular deconditioning due to fluid shifts, orthostatic intolerance
Fluid balance	Diuresis and decreased plasma volume	Fluid retention due to increased hydrostatic pressure	Fluid shifts to the upper body, resulting in reduced plasma volume
Haematological response	Elevated haematocrit, increased blood viscosity	Risk of oxygen toxicity leading to altered haemoglobin function	Altered blood viscosity, reduced erythropoiesis
Cellular metabolism	Hypoxia induces anaerobic metabolism and lactate production	Oxidative stress, reactive oxygen species production	Altered protein synthesis and mitochondrial dysfunction due to microgravity
Gas kinetics	Decreased oxygen saturation, increased risk of hypoxia	Inert gas dissolution in tissues increases the risk of narcosis and decompression sickness	Gaseous fluid shifts and increased risk of dehydration and hypoxia
Sleep	Impaired sleep quality due to hypoxia	Sleep disturbances due to pressure and oxygen levels	Disrupted sleep cycles due to microgravity effects on circadian rhythms
Musculoskeletal Effects	Decreased muscle mass, fatigue and reduced endurance over time	Pressure-induced atrophy, altered muscle function	Muscle atrophy, bone density loss due to microgravity
Thermoregulation	Impaired thermoregulation, susceptibility to hypothermia or heat stress	Cold or heat stress due to pressure changes	Thermoregulation is challenged due to fluid shifts and environmental extremes

[Table/Fig-1]: Comparison of the physiological effects across high-altitude, hyperbaric and space environments, highlighting key differences in how each setting impacts various bodily systems [1,5,8,10,13-16].

Anaesthetic Challenges in Resource-limited Settings

Anaesthesia in resource-limited settings presents several challenges that must be addressed through improvisation, adaptation and risk mitigation. The first is limited access to key medications, including inhalational anaesthetics, neuromuscular blockers, or local anaesthetics. The supply chains are not trustworthy and stockouts or poor-quality drugs are the new norm. The second problem is inadequate equipment and monitoring devices. Anaesthesia machines, ventilators, or stable power may not be available in the operating rooms. Basic monitoring, such as pulse oximetry, capnography, or continuous blood pressure monitoring, may be unavailable or only intermittently available. Perioperative mortality rates in low-resource areas are significantly higher compared to high-income settings, often due to the lack of essential anaesthesia and perioperative care. Limited access to safe anaesthesia increases the risk of complications such as inadequate ventilation, unrecognised hypoxia and cardiovascular instability, contributing to poor surgical outcomes and higher mortality. These trends underscore the critical importance of enhancing anaesthesia safety and resources in these regions to reduce avoidable deaths and improve surgical outcomes [17,18].

Staff shortfalls are another paramount issue. There can be a deficiency in trained anaesthetists or nurse anaesthetists and providers often find themselves compelled to work outside their area of expertise. Training in challenging airway management, difficult intubation, or regional anaesthesia is inadequate; ongoing education or mentorship is the exception. The absence of suitable diagnostic equipment, laboratory assistance, or time availability could undermine preoperative evaluation. Patient co-morbidities can be uncontrolled or unrecognised and hence expose the patient to a high-risk of complications. Postoperative care and recovery facilities are often suboptimal. Intensive care is limited, nursing or monitoring is poor in recovery rooms and there is a failure to deal with complications such as airway obstruction, bleeding, or respiratory failure. Transport or evacuation facilities for deteriorating patients are slow, expensive, or unavailable [2,3,17,19].

Resuscitation Strategies in Austere Environments

Resuscitation in the austere setting involves prioritising suitable, effective and robust interventions in the face of numerous constraints. Blunt haemostasis of any visible bleeding is a principal aim. Tourniquet application, haemostatic dressings or powders and pressure are valuable in reducing haemorrhage. With facilities or staff allowing, methods such as Resuscitative Endovascular Balloon Occlusion of the Aorta (REBOA) can be employed to arrest temporary non compressible haemorrhage and gain time for definitive treatment. REBOA involves occluding the aorta using a balloon catheter to control haemorrhage, particularly in cases of pelvic or lower limb trauma. REBOA can improve short-term survival by stabilising patients in haemorrhagic shock, especially in austere environments. However, it carries risks such as ischaemia and organ injury with prolonged occlusion. Fluid resuscitation must be tailored according to what is available, with the minimum amount of crystalloids and employment of plasma, whole blood, or lyophilised product where accessible to maintain volume, coagulation and oxygenation. Early antifibrinolytic therapy, like tranexamic acid, is required in trauma. Intraosseous access is a good alternative when vascular access is hard or delayed. The majority of sites where rescue fluids can be supplemented or substituted by enteral or oral resuscitation fluids, particularly in cases of burn shock or intravenous fluid absence [1,20,21].

Maintenance of core temperature is critical because hypothermia worsens coagulopathy, metabolic acidosis and mortality. Oxygenation and ventilation should be sustained as soon as feasible, provided that this may not always be feasible with full mechanical ventilation. Fundamental airway and ventilatory support with bag-valve masks or other handheld devices can be life-sustaining. Resource-limited resuscitation algorithms must be minimised and optimised to meet the requirement for an expedient decision. The “damage control” concept can be used to immediately resuscitate life-threatening issues, delay non life-threatening procedures and emphasise cost-saving interventions. Monitoring may be kept to the bare essentials, so clinical presentation dictates therapy. Guidelines and training should be based on improvisation, redundancy and contingency. Transport time, evacuation time and communication constraints must be taken into account from the start [22,23].

Anaesthesia and Resuscitation at High Altitude

High-altitude subjects and health providers are exposed to an atmosphere of hypobaric hypoxia, in which the inspired air oxygen partial pressure decreases with increasing altitude. Therefore, oxygen saturation in the arteries decreases unless balanced by an increase in minute ventilation. Respiratory effort becomes enhanced at the expense of gas exchange, leading to increased risk of ventilatory failure in vulnerable patients. Pulmonary vascular resistance rises with an increase in pulmonary hypertension and in extreme cases, fluid can leak into alveolar spaces and result in high-altitude pulmonary oedema. Cardiovascular function is also strained: heart rate and cardiac output rise acutely, but basal stress may cause right heart strain. Haematologic alterations, including an increase in red blood cell mass, occur within weeks to days but are associated with the risk of elevated blood viscosity. Dynamics of fluid balance, such as plasma volume reduction, renal compensation for acid-base derangement and risk of dehydration, occur. These changes modify the margin of safety for anaesthesia and resuscitation. The anaesthetic dosage must be adjusted to change the pharmacokinetics [14,15,24].

Low ambient pressure alters the vapour pressure of volatile agents, impacting their absorption and distribution. The Minimum Alveolar Concentration (MAC) of volatile anaesthetics decreases with increasing altitude. As atmospheric pressure falls, the partial pressure of anaesthetic gases in the lungs is lower, which requires a decrease in the MAC to achieve the same anaesthetic effect. This means that less anaesthetic agent is needed to achieve the desired depth of anaesthesia at altitude compared to sea level. Agents inducing respiratory depression or concealment of compensatory hyperventilation should be employed with caution. Preoxygenation should be utilised due to the risk of rapid desaturation. Regional anaesthesia, when feasible, can be the preferred technique for preventing airway manipulation. Onset time, duration and haemodynamic impact could be altered at sea level. Monitoring will be attentive to hypoxemia, ventilation-perfusion mismatch and haemodynamic instability. Equipment calibrated at sea level may also respond differently at altitude. Resuscitation at high altitude requires preparation for delayed rescue, restricted facilities and heightened physiological stress [14,25].

Cardiopulmonary resuscitation is more taxing for rescuers due to the increased metabolic demand from hypoxia and cold. Defibrillation, airway control and vascular access are potentially more difficult to obtain consistently. Oxygen supplementation is even more important; room air is less effective and less accessible if no increased inspired fraction is present. Fluid resuscitation needs to be tailored to prevent further increase in pulmonary oedema. Maintaining core temperature, avoiding over-sedation and monitoring for altitude illness, such as high-altitude cerebral or pulmonary oedema, are essential adjuncts [26-28].

Considerations in Space and Space-analogue Environments

Microgravity, confined spaces, isolation and altered life support dynamics present a series of challenges to resuscitation and anaesthesia that are unique to the environment of space and space-analogue environments. Microgravity is characterised by upward fluid redistribution, elevated central venous pressures, cardiovascular deconditioning, decreased orthostatic tolerance and changed baroreflex sensitivity. These alterations compromise haemodynamic stability during induction, positive-pressure ventilation, or volume shifts. Respiratory mechanics are impaired due to lost lung volume and altered ventilation-perfusion relationships in the absence of gravity. The pharmacokinetics of drugs, including absorption, distribution, metabolism and excretion, can be influenced by changes in plasma volume, organ perfusion and renal function. Physiology at the neuromuscular junction also changes with deconditioning and neuromuscular blockers must be changed and closely monitored. Technical and procedural limitations increase risk [2,29].

Airway management is more difficult due to the absence of consistent anatomical reference points, mucus floating and positioning issues. Equipment used for managing fluid and gas handling in earth gravity often fails to function- fluid bags cannot be distinguished from air bubbles, suction is gravity-dependent and vapourisers do not perform as predicted. Closed cabin environments restrict the use of volatile agents due to contamination and fire risk concerns; therefore, total intravenous anaesthesia becomes the preferred option. Telemedicine support is restricted by latency in remote communications, necessitating independent decision-making and strong decision support. Medical staff is not necessarily thoroughly trained in anaesthesia and thus, processes should be kept simple, automated and based on redundancy and cross-training. Team training, equipment testing and protocol fine-tuning require simulators and Earth analogues (e.g., underwater labs, polar stations) [16,30].

Anaesthetic and Resuscitative Complications in Hyperbaric and Underwater Environments

Submarining and hyperbaric environments present special challenges to resuscitation and anaesthesia because of the higher ambient pressure and the body's reaction to it. Higher partial pressures of oxygen are known to lead to oxygen toxicity of the central nervous system and lungs and thus require careful monitoring and control of oxygenation. Pressure also alters the pharmacokinetics of anaesthetics, necessitating adjustments to dosing and administration. Patency of the airway and adequate ventilation in a volume-expanded or closed space complicate matters and conventional anaesthetic techniques may need to be modified to avoid pressure-induced complications. Resuscitation under these conditions is limited by compromised access to the patient, limited room space and the need for specialised equipment. Cardiopulmonary resuscitation must be adjusted to consider buoyancy and environmental limitations; defibrillator or other device use may be restricted. Ventilation and airway management techniques must be adjusted for submerged or pressurised environments and early detection of complications is crucial. Real-world rescue scenarios, such as those from deep-sea diving or hyperbaric oxygen therapy centres, have highlighted critical lessons in anaesthesiology. For example, during a deep-sea diving accident, the use of conventional anaesthetic agents led to severe complications due to altered pharmacokinetics at high pressure, emphasising the need for modified dosages and careful oxygen management. In hyperbaric chambers, rapid decompression during resuscitation has caused barotrauma to patients, stressing the importance of controlled ventilation and gradual pressure adjustments. Preparation and training must be guaranteed so that healthcare staff can best handle hyperbaric or underwater emergencies [5,28,31-33].

Equipment Restrictions and Innovative Solutions

Equipment limitations control the delivery of resuscitation and anaesthesia in remote, austere and extreme environments. Routine equipment and monitoring devices could be unavailable, unreliable, or inappropriate for the environment. At high altitudes, lower oxygen pressures and potential equipment malfunctions due to low atmospheric pressure can impair the accuracy of monitoring devices, such as pulse oximeters and capnographs. Electric power is interrupted, sterile processing is restricted and equipment designed to operate at standard atmospheric pressures could fail under high pressure, temperature, or humidity. Underwater, additional challenges include waterproofing and maintaining functionality in submerged environments, where pressure increases with depth and can cause devices to fail or become less accurate. In microgravity, where traditional blood pressure cuffs and oximeters are less effective due to fluid shifts and reduced gravity, alternative techniques such as wearable sensors or continuous monitoring may be necessary. Miniaturised or portable equipment is often required but may offer diminished capability compared to conventional systems. Oxygen saturation, end-tidal carbon dioxide, blood pressure and other critical parameters can be incomplete or intermittent, with additional clinical assessment and judgement required. Improvisation training and backup planning enable personnel to creatively adapt equipment without jeopardising patient safety. Sterilisation also poses a challenge in these environments, especially in high-risk settings where traditional autoclaving or chemical sterilisation methods may be unavailable. Low-resource reprocessing techniques, such as cold sterilisation or ultraviolet light exposure, are often used to manage equipment decontamination in the absence of conventional methods [2,34].

Pharmacologic and Monitoring Adaptations

Extreme and harsh environments modify the body's absorption, distribution, metabolism and elimination of drugs, making regular dosing and timing less predictable. Hypoxia, pressure changes, altered fluid distribution, dehydration and changes in organ perfusion can all modify the pharmacokinetics and pharmacodynamics of anaesthetic, analgesic and resuscitation drugs. Drugs that inhibit respiration, blunt cardiovascular responses, or exhibit tight windows for tolerance to accepted therapeutic doses must be titrated well and monitored intensively. Regional anaesthesia is employed when systemic effects are hazardous; however, the onset and duration depend on local tissue perfusion and temperature. At high altitudes, the onset of neuraxial anaesthesia may be delayed due to reduced local tissue perfusion and the dose required may vary, requiring careful titration. The decrease in barometric pressure and oxygen availability can alter the pharmacodynamics of local anaesthetics, potentially necessitating higher or more frequent doses for effective anaesthesia. Monitoring facilities in such environments are usually less than ideal. Routine continuous oxygen saturation, end-tidal carbon dioxide, blood pressure and electrocardiography monitoring may be absent, sporadic, or interrupted by environmental conditions. Newer, field-appropriate monitoring technologies such as portable ultrasound, wearable biosensors and wireless electrocardiograph monitors have shown promise in remote settings. For instance, a study on portable ultrasound devices in austere environments highlighted their utility in assessing fluid status and cardiac function without the need for bulky equipment. Physicians must depend on clinical presentation and simple, rugged, transportable and battery-powered devices. Capnography and pulse oximetry, though essential, can be less reliable in extreme cold, as peripheral vasoconstriction may lead to inaccurate readings in low temperatures. Condensation and fogging in equipment can interfere with accurate monitoring. Inventions such as wearable sensors, point-of-care blood testing and filtered telemetry enable remote or continuous monitoring without the need for regular machinery. Protocols must be revised to emphasise the early recognition of impairment, redundancy in observation and synergy between technological and human observation, thereby providing safe anaesthesia and resuscitation [1,3,35].

Support for Training, Simulation and Telemedicine

Effective resuscitation and anaesthesia in extreme, austere and forward locations rely strongly on advanced preparation and training. Staff generally encounter uncommon physiological challenges and limited equipment and resources; therefore, traditional clinical practice is inadequate. Simulation training enables practitioners to simulate procedures, diagnose equipment faults and practice emergency protocols in a realistic yet controlled environment. High-fidelity simulators, virtual reality modules and environment-based exercises enable the development of competence, confidence and decision-making ability under stress. Training models specifically validated for austere conditions have been developed to address the unique challenges of remote or extreme environments. For example, high-fidelity mannequins designed for low-resource settings allow practitioners to perform lifelike procedures with limited equipment. Virtual reality modules designed for high-altitude, underwater, or hyperbaric environments enable users to practice decision-making and procedural skills while experiencing simulated environmental stresses, such as oxygen deprivation or pressure changes. Such models have been validated in military and disaster response training and have been shown to improve performance in real-world emergencies. Telemedicine offers life-critical support when specialist guidance is not physically present. Remote control, live video guidance and decision-support software enable less qualified practitioners to carry out high-intensity interventions safely. Delays in communication, bandwidth availability and ambient conditions must be accommodated and procedures are modified to permit independent decision-making when concurrent assistance is unavailable. Serious training, simulation courses and telemedicine care enhance readiness, increase procedural skill and reduce the risk of complications in anaesthesia and resuscitation in austere and remote locations [1,2,36-38].

CONCLUSION(S)

Anaesthesia and resuscitation in austere, remote and hyperbaric environments face unique challenges due to physiological stressors, limited resources and environmental extremes. Understanding altered human physiology, adjusting pharmacological approaches and creatively using available monitoring equipment are essential. Flexibility in clinical protocols is crucial to adapt to these constraints. Training, simulation and telemedicine play a vital role in preparing staff for emergencies when expert assistance or evacuation is not possible. Advances in portable, rugged technology and interdisciplinary collaboration further enhance safety in these environments. By applying lessons from high-altitude, underwater, hyperbaric and space analogues, clinicians can develop strategies to improve patient outcomes. Ongoing research and protocol refinement are needed to address knowledge gaps and optimise care in these high-risk settings.

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