Tobias Cibis
Carolyn McGregor *Editors*

Engineering and Medicine in Extreme Environments

Springer

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To those who are curious about the extremes
of this world and beyond.

Foreword

I watched with interest as my crewmate prepared to draw my blood for one of the many research experiments that was part of the mission. Throughout training and during the mission, each of the crew had experienced what seemed like innumerable blood draws and had become used to having samples taken. This would be one of the final draws for me as the 16-day research spaceflight called Neurolab was coming to a close. We would soon be back home sharing stories about the incredible experience of flying in space. For now, we were focused on success, and as the test subject, I was hoping that the sample draw would be successful.

Drawing blood in space is somewhat similar to performing the procedure on Earth in that either an angiocath needle and catheter combination or a smaller butterfly needle is inserted into a forearm vein. Successful insertion is rewarded with the appearance of blood in whichever device is used and everything is immediately taped in place to prevent the catheter coming out of the vein. In microgravity, everything else is different. Each of the many items needed, the alcohol and iodine wipes necessary to cleanse the skin, the gauze squares, the tape, the catheter, the sterile covering for the catheter, and the different tubes, cannot be organized neatly on a bedside table. In microgravity, unrestrained items quickly float away, a potential source of frustration and wasted time for the crew performing the procedure as they try and find the lost items. To prevent this from taking place, we used a technique called the reversed grey tape temporary stowage technique.

Grey tape seems to be ubiquitous when humans are living and working in extreme environments. Space is no exception to that rule. To manage all of the items needed to insert an intravenous (IV) catheter, we would cut a strip of grey tape around two feet long. It was then attached sticky side out to the front hardware rack adjacent to the site where we would perform the blood draw by attaching 3 inches of tape to the rack then flipping the tape back over itself and repeating the sequence at the other end. If done correctly, it provided roughly 18 inches of a sticky surface that we could use to attach everything we needed in the sequence it would be used. The technique was elegant in its simplicity, did not involve any high-tech hardware and worked flawlessly.

My colleague prepared the skin of my forearm with the alcohol and iodine swabs, the distended veins prominent as the tourniquet blocked the blood flow returning from my arm. Without gravity, we have to rely on the tourniquet to see the veins. My veins are normally easy to see, but this time they weren't as prominent as normal. Perhaps I was dehydrated, or the previous blood draws had affected them, and as a physician looking at them, it appeared that it would be slightly more difficult than usual for my colleague to insert the IV. "Are you ready?" they asked. "Go ahead" I responded, not particularly concerned about how this would go. Unfortunately, the attempt was unsuccessful as was the next and the one after that. With one catheter remaining in our inventory, I was hoping for success, but the last attempt was similar to each of the previous ones. We proceeded without the specimen.

This experience illustrates a few of the challenges in providing medical care in extreme environments. Inventory is limited, skill proficiency changes over time, and the environment itself presents challenges to care providers who generally have minimal support in solving whatever problems they face. Those who venture forth to explore and work in these often, hostile circumstances understand the truth in the saying "an ounce of prevention is worth a pound of cure." Ideally, prevention can mitigate the risk of illness or injury; however, the very nature of extreme environments is the increased risk of a medical event. If that were not the case, they would not be called "extreme."

Throughout history, humans have generally lived in regions of the Earth where it is warm, water abounds, and the air pressure makes breathing easy. As technology improved, humans began living in more inhospitable climates, although roughly 40% of the world's population still live within 100 km (60 miles) of a coast while 33% live at altitudes of less than 100 m. Living and working in the two final frontiers, space and the undersea world, and other extreme environments is difficult. It requires sophisticated life support systems, specialized communication equipment, food, and inventory resupply.

The very nature of the different environments is usually associated with some physiologic adaptation whether it is living at altitude, in the ocean, at the poles, or in space. Extreme environments challenge the resilience of humans, test their ingenuity, and make them reliant upon technology for success. Many shy away from such challenges, but there are those who routinely work or challenge themselves in isolated places where variations of temperature and pressure are an ever-present physiologic stress, where wilderness and climate require specialized skills, perhaps exploring or sometimes rescuing, in times of peace and conflict. When bad things happen, they understand they may have the rest of their lives to solve the problem.

Living and working at the "edge" requires a unique blend of engineering, leadership, teamwork, training, proficiency, strategies to control risk, and a focus on wellness as well as the availability of routine and emergency healthcare. Understanding how humans adapt and thrive in such environments, and monitoring and detecting changes in their physiology, performance, and behavior are an important element of survival, let alone success. Readiness is critical. It depends upon research to understand how humans function in extreme environments and technology development to help them thrive in those environments whether for recreation or professional pursuits. Controlling risk is based on optimizing adaptation, understanding the human factors associated with team performance, and developing new technologies.

Engineering and Medicine in Extreme Environments, co-edited by McGregor and Cibis, is an excellent overview of the technical and clinical challenges associated with living and working in extreme environments and a must read for those interested in controlling the risks associated with living and working there. The book effectively blends the story of physiological and psychological adaptation in extreme environments on Earth and the two final frontiers of space and the undersea world. The discussion of new wearable technologies, information technology, and the role for artificial intelligence in helping monitor and detect physiologic decompensation, illness, or injury is particularly important in extending the limits of human performance.

Throughout history, humans have pushed the limits of exploration on Earth and in space. As we continue to learn about our own planet, to understand planetary stewardship and the need to protect the planet for future generations, we have set our sights once again on the Moon. Since 2000, there has been a continuous human presence in space with humans living and working aboard the International Space Station, the beginnings of a new phase of sustained human space exploration that will forever mark the start of this millennium. Working and thriving in extreme environments is the ultimate competency-based challenge for teams. It requires a unique collaborative, multidisciplinary blend of expertise ranging from engineering to medicine, and this book provides the perfect starting point to begin understanding the challenges of the journey from exploring the extreme environments on Earth to follow a path that will ultimately lead back to the Moon and one day on to Mars. Enjoy the journey!

Toronto, ON, Canada
April 2021

David R. Williams

Preface

The world around us imposes strict limitations on human physiology in many ways through physical quantities prevailing in those environments. These physical quantities can be considered as extreme when abnormally high or excessive exposure to any of the following occurs: cold, heat, pressure, vacuum, voltage, corrosion, chemicals, particles and electromagnetic radiation, vibration, shock, moisture, contamination, dust, or extreme fluctuations in operating temperature range.

There is a certain attractiveness in conquering the extremes of nature in this world and beyond. Whether it be climbing the highest mountains, deep diving into the undersea world, exploring space, or being exposed to the heat of deserts or arctic cold, humans follow their curiosity into these extremes.

The first steps into these extreme environments were taken by pioneers who often tested the limits of their life while making history. Motivations for conquering extremes are many and include curiosity, hope for future colonization, the potential of new resources that can be harnessed, and humanitarian and defense efforts. Over time what was thought to be extreme may become more within the bounds of normal, driving humanity to constantly refine what is considered extreme.

Some of the greatest accomplishments in exploration over the last few centuries in extreme environments were performed by Roald Amundsen and Robert F. Scott with their race to the South Pole (1911–1912), Jacques-Yves Cousteau through his adventures into the deep sea (1962–1965), Neil Armstrong as the first person to set foot on the moon, or Reinhold Messner climbing the largest mountains on the Earth's surface (1970–1986). Each of these pioneers likely experienced their limit of bodily functions to overcome the effects of microgravity, to counteract the increased ambient pressure, deal with hypoxic atmosphere, or to maintain inner body heat in the arctic cold. If not for the dynamic range of human functional physiology including the capability to adapt to ever changing external conditions, then these milestones in exploration would not have been reached.

Although humans are capable of exploring and even living in any austere environment, it sometimes requires a significant amount of time to adapt or great technological and logistical efforts to ensure survival. However, the actual range of environmental conditions humans can comfortably live in is relatively narrow.

Any of the physical types of extremes can be responsible for triggering compensatory physiological response mechanisms both directly and indirectly. Being attuned to external changes ensures survival. This fascinating synergy between physics and physiology is the core objective explored in this book.

Modern advances in sensing and monitoring technology as well as techniques in machine learning and artificial intelligence enable a whole new range of opportunities to monitor, analyze, and assess environmental effects on human physiology.

This book investigates the synergy and interconnections between the triangle of physics, medicine, and technology. Combining all three leads to new ways to collect and analyze physiological data in extreme environment conditions to help us understand how the human body works in these extreme situations.

New knowledge, modern technology designs, and predictability of exposure procedures may all be driving factors to further increase our capabilities for exploration and satisfy our curiosity to learn about the unknown.

Given the strong interdisciplinary nature of this book, covering physics, medicine, and technology, sometimes only a brief overview of certain concepts is provided as a collection of medical, engineering, and computer science approaches. Any reader that is seriously interested in more extensive studying of physiology or engineering should be encouraged to follow up on the literature which is referenced within the different chapters of this book.

The intention for this book was not to create a textbook for physicians to study the medicine and physiology of extreme environmental exposure. Nor was it to provide a full mathematically heavy engineering book to study the concepts of electrical engineering or information sciences. Nor was it to completely document the details of the professions whose role it is to function in these extremes. In the nature of interdisciplinary efforts, the intention was to locate this book somewhere in between, making it interesting and informative for a diverse group of researchers and educators.

This book can be used in multiple ways by different research and education professionals. Engineers may use this book to consult on physiological, medical, and profession-based concepts and knowledge of biological responses to extreme environments. A fundamental knowledge about the biomedical principles and professions they wish to serve can prove to be beneficial for successful technology design. Thus, technology can be adjusted accordingly towards the requirements dictated by medicine and the profession. Physicians may use this book to learn about and understand the concepts of different technologies and information system approaches to collect and analyze data. This may provide complementary or new approaches for medical researchers to advance their research efforts. Furthermore, this book can be used in educational settings as a supplement to traditional course material in medicine, engineering, or science.

The content of the book is presented in two parts per extreme environment. The first part is devoted to introducing the environment and its prevailing conditions, together with the corresponding physiological challenges, adjustments, and adaptation mechanisms. These chapters also present information about the job function for the various professions that operate within these extreme environments. The second part focuses on technological advances that align with to the requirements that arise due to the environment and physiological responses that need to be monitored. For example, the monitoring of cardiovascular functions in an underwater setting requires specific sensor designs to enable operability in the austere environment. It should be noted that a technology presented with respect to a specific environment is not limited to such, but often finds potential application in a variety of different settings. This book simply presents individual technologies in the scope of a specific scenario, for example, ultrasound technology for battlefield application or virtual reality for elite athletes training. Obviously, these technologies can also be applied for other purposes; however, the fundamental concepts introduced would remain the same.

Although the book covers many different environments, medical phenomenon, and technological approaches, it (unfortunately) falls short in covering all the extreme diversities which can nowadays be observed and experienced on this planet and beyond. The complex interplay of environment, physiology, and technology has many facets, and enlightening all of them would by far exceed the properties of a single book. However, this is a clear indication about the fascinating heterogeneous and continuously advancing research opportunities that rise from studying these interdisciplinary complexities.

Enjoy reading.

Sydney, NSW, Australia Tobias Cibis
Oshawa, ON, Canada Carolyn McGregor AM
March

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This book was created in the midst of the Covid-19 pandemic in the year 2020. All contributors, authors, and peers went to great lengths and efforts during these extraordinary and bizarre times. A great *thank you* to all of you for proving that dedicated work can overcome any extreme.

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Part I
Fundamentals

Chapter 1
The Physiological and Psychological Environment in Humans

Tobias Cibis and Carolyn McGregor AM

1.1 The Nature of Human Boundaries

Human beings are among the most adaptable creatures on the planet's surface, yet natural and unnatural extreme conditions impose significant narrow limits to human survival. The comfortable environment for humans is mostly geographically constrained because latitude and topography create extreme variations in temperature, barometric pressure, availability of food, and water, or a combination of each that are critical for survival [1]. Survival can be defined in terms of interactions between an individual and its natural surroundings. Being alive requires constant adjustment to environmental changes and stressors. Many organisms, among them humans, are particularly sensitive to even small changes in environmental conditions.

The nature of inhospitable environments is imposed by the behaviour of prevailing physical conditions. If changes in one or multiple conditions occur, such as exceeding extreme high or low limits, or significant fluctuations occur, the life of an organism can be endangered (Fig. 1.1). Extreme highs or lows can occur due to natural disasters. Blizzards, flooding, or bush fires generally result in a significant change of environmental conditions, making a once hospitable area inhospitable. Significant fluctuations, such as the temperature range in the day–night cycle in

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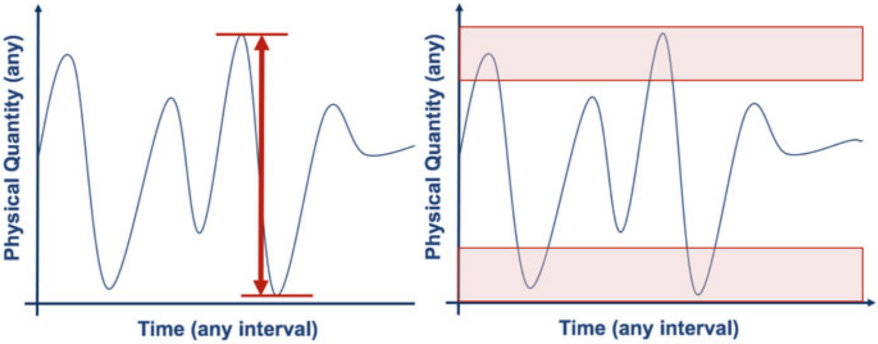

Fig. 1.1 Physical quantities and their constitution of a critical condition to organisms' physiology. Physical quantities can be considered as harmful when they reach a critical high or low extreme (**a**) or when there is a rapid fluctuation and oscillation (**b**). These extremes and fluctuations can become more complex in the interaction of multiple physical quantities with another

deserts, demand constant extreme adaptations. These continuous adjustments may not be carried out over a long duration and can become too demanding for an organism [1].

Although there are two fundamental forces, gravity and electromagnetism, that we can perceive with our senses, these two congregate a large number of other physical quantities: temperature, density, pressure, acceleration, depth/height, humidity/dryness, solubility, saturation, radiation, toxicity, and many more. These quantities, in varying composition and intensity, derive the conditions that forge the diversity of the biosphere around the planet's surface and beyond.

Physical quantities are not only responsible for shaping the universe but also have a direct impact on anatomy and physiology of an organism. Gravitational force, for example, limits the maximum size of an organism. Animals cannot grow, or be scaled up to an extraordinary size, without breaking under their own weight. Hence elephants developed large legs to support their weight. Aquatic mammalian animals rely on surfacing intervals to breathe. To increase underwater time, they reduce their heart and metabolic rate, which results in a decrease in heat production.

All living spaces have physical boundaries within which life is possible and outside which life is considered impossible. If conditions depart towards a limit, life is only sustainable with increasing effort. The greater the external stress, the more vigorous must be the attempt of compensation. However, if compensation falls short, the survival time may be shortened significantly.

1.2 Physiological Environment in Humans

The most important characteristic of every living organism is its ability to maintain an active equilibrium with its environment. All living organisms attempt to maintain constant internal conditions in the face of changes in the environment [1]. Ideal internal conditions allow an organism to regulate health and comfort, and to perform daily tasks at an optimal level. However, exposure to extreme environments through exposure to extraordinary physical and psychological stimuli triggers a disruption of the internal conditions. In order to ensure survival the body needs to respond and initiate regulatory mechanisms to compensate for the disruption.

1.2.1 Homeostasis

The idea of a physiological regulatory concept was first introduced in 1965 by Claude Bernard, who recognized that the human body generates an internal environment, the *milieu-intérieur* to regulate and sustain life [2]. His conclusion was that the human body always pursues the one goal, to maintain uniform conditions of internal life. Extreme conditions should be avoided and are always regulated towards an optimal mean. Bernard's idea was later extended by Walter Cannon who specified regulation mechanisms and named the concept *homeostasis* [3]:

> Before those extremes are reached agencies are automatically called into service, which act to bring **back towards to mean position** the disturbed state. [...]
> Such disturbances are normally kept within narrow limits, because automatic adjustments within the system are brought into action and thereby **wide oscillations are prevented** and the internal conditions are fairly constant.

Cannon's description includes two fundamental mechanisms of homeostasis; "back towards mean position" indicates negative feedback mechanisms as a regulatory control, while "wide oscillations are prevented" suggests the pursuit of internal stability. He further communicated the idea that failing regulatory mechanisms, hence the failure of maintaining a homeostatic state, is likely to result in death [4].

Derived by the findings from Bernard and Cannon, homeostasis is the pursuit of stability of physiological systems that are essential for life. These systems, such as body temperature, glucose levels, oxygen tension, cardiovascular activity, and more, are maintained within a range ideal for the prevailing life stage. The concept of homeostasis can be applied to understanding both normal physiology and diseases. Attenuated homeostatic responses are not only results triggered by environmental stimuli but also occur as a consequence of disease processes [1]. By definition, a disease disrupts homeostasis in one way or another. Thereby, one compensatory response may resolve one disorder while creating another. It needs to be considered that some adaptations are maladaptive.

In order to simplify the complexity of functional system homeostasis, modern research approaches assessing physiological systems tend to operate within a narrower frame of reference than that of homeostasis [1]. The body is reduced to a group of systems or an individual system, each containing a set of regulatory and functional mechanisms. These components are often described by specialized terms, such as set point, negative feedback loop, and gain.

The basic regulatory process is essentially the same for each system: An environmental stimuli affects a physiological parameter that consequently requires regulation; a detector that measures the parameter; a comparator determining the difference between a designated set point and the current value; and a compensatory response to balance the difference. The greater the stimuli and subsequent distortion from the set point, the greater will be the compensatory response, which is represented by the gain. The gain also determines how rapidly the parameter returns towards the set point, completing the feedback loop. As the actual value of the parameter approaches the set point, the compensation intensity diminishes.

An interesting example of physiological regulation to maintain a homeostatic state in the scope of extreme environment exposure can be found in both scuba divers and astronauts [5, 6]. Both of which are facing a similar physiological phenomenon in their specific environment. While divers are exposed to an increased ambient pressure, astronauts find themselves exposed to microgravity. The increased ambient pressure triggers a peripheral vasoconstriction, a tightening of peripheral tissue and vessels. In space, the circulatory system is impacted by zero gravity and the absence of vertical workload resulting in a lack of force on the blood towards the extremities. Both situations result in an increased blood volume shift to the central body. Subsequently, the body recognizes a hypervolumetric state and starts to compensate the disruption of homeostasis. Increased central blood volume and cardiac volume stimulates atrial receptors to release atrial natriuretic factors (ANFs) in response to stretching, which, in addition to an associated decrease of anti-diuretic hormone (ADH), triggers the renal system. The renal system initiates an unopposed diuresis to reduce the total body fluid volume and to reinstate the internal equilibrium.

This observation provides several interesting aspects of environmental stresses and homeostatic regulation. Diving and space exploration exposes subjects to the exact opposite sides in the scope of the predominant environmental force, diving with an increased ambient pressure due to the higher density of water compared to air, and space with almost no acting force as a result to microgravity. However, the regulatory compensation to both is similar. This may be due to the fact that the determining factor of regulatory compensation is not the initial stress, but rather the unfolded cascade of multiple physiological systems, transforming the disruption into secondary physiological system abnormalities that are more efficiently regulated enabling compensatory resources of different systems to be shared. Thus, it is often difficult to associate certain sensor and response mechanisms to specific external stimuli, due to the complexity and interaction of multiple physiological systems.

This also presents shortcomings of the homeostatic concept. Homeostasis has merit to assess and evaluate the immediate extreme environment exposure when a direct feedback response is required. Mechanisms of physiological systems using set points and negative feedback have been useful in assessing homeostasis. However, such approaches fail to explain how homeostasis is maintained over the long run. The premise to preserve a constant set point was pointed out not to consider dynamic changes, which would require the adjustment towards a new set point. Instead, it has to be assumed that there is a range of set values, which serve to expand the effort for regulatory systems. Efficient regulation requires anticipating needs and preparation based on past experiences. This regulatory strategy requires a dedicated organ, the brain.

1.2.2 Allostasis

While homeostasis identifies immediate causes, allostasis suggests a much broader approach to regulatory adaptation. Allostasis describes the regulation to anticipate needs and preparations to satisfy them before they arise. It can be noted that allostasis achieves stability through change. This means that the *set point* and other control constants are subjected to changes.

The systems that are essential for the stability of life (*homeostasis*) can be distinguished from those systems that maintain a dynamic balance of the prior systems (*allostasis*) [7]. Thus, allostasis extends homeostasis to include a feed-forward anticipation, behaviour, and brain–body interaction, which may contribute to variable dynamics [8], providing opportunities to expend effort in their pursuit, including responses to predictable changes, e.g., seasonal, and unpredictable changes, such as natural disasters [7]. Allostasis incorporates benefits, which are not in the scope of homeostasis: errors are reduced in magnitude and frequency; response capacities of different components are matched in order to prevent bottlenecks and reduce safety factors; resources are shared between systems to minimize reserve capacities; and errors are remembered and used to reduce future errors [7, 8].

There are potentially two complementary views of allostasis. One involves how organisms in their environment satisfy their evolutionary needs for food and shelter, and thereby enhancing overall fitness. This would require the orchestration of daily and seasonal needs in relation to environmental conditions and unpredictable changes in environment. Failure to deal with these occurrences leads to death. The second view involves the impact of complex social structures on human health and longevity of its members under conditions where social organization predominates over basic needs as a factor that causes stress. Physiology on the one hand and psychology on the other both have some common ground in the concept of allostasis and mechanisms underlying coping with environmental stressors [7].

It may also be applied on a cross-level, connecting individual physiology to social behaviour to survival strategies. In human nature, being intensely social requires higher cognitive functions to interpret and predict environmental stimuli. Our capacities for love, deception, and treachery, plus our needs for apology and reassurance, depict a strong match to maintain social stability [7]. The concept of allostasis may also support the idea that health is intimately connected with placating spirits through maintaining communal relationships.

1.2.3 The Concept of Adaptation

In the literature, there is a large variety of research describing the terminology of adaptation, acclimatization, and adjustment [9–13]. A standalone definition for each term is difficult to find. This may be due to the fact that the concepts these terms try to comprise are extremely complex scenarios that come with many variations and components depending on the individual assessment approach. Some authors suggested that adaptation serves as an all-inclusive or umbrella term, while others recommended that the definitions of the terminologies should be adapted on a case by case basis by researchers in their specific fields. It is sometimes difficult to distinguish between adaptation and acclimation as their definitions overlap.

Although individual publications utilize and adjust these terms to fit their purpose, there are several key ideas that can be attributed to a specific term. Usually there is a clear differentiation of the duration and intensity where changes are in progress. Thereby, processes that take an extended time to manifest are considered as adaption processes, whereas faster occurring processes are attributed to acclimatization. Another distinguishing feature can be the circumstance that initiates the adaptational process.

The terms are often described with an additional predicate. Thus, common distinctions are biological adaptation, physiological adaptation, and sometimes psychological or social adaptation, thereby specifying the biological or mental systems that are subjected to change [1, 3, 11]. Application areas may also have an impact on which kind of definition is predominant. Commonly, this is dictated by the prevailing usage in the literature and day-to-day communication. Thus, in daily use, people say that they acclimated to different temperatures when climate zones changed or that their eyes adapted to different light brightness. Despite all the differences in definitions and descriptions, it resonates that both adaptation and acclimatization are processes that fundamentally require a multitude of bodily systems to act.

It is therefore important to note a general definition of the terms adaptation and acclimation, as those concepts will be referred to frequently in the following chapters in this book.

Adaptation

Although there are several definitions present in the literature, throughout this book, adaptation addresses the adjustments in biology and physiology for both short- and long-term changes [10, 11]. The fundamental processes comprise the development of adaptive mechanisms that protect the human body from failure due to changing environmental conditions, by establishing performance at a (metabolically) comfortable level, and to regain a new homeostatic level fitted to the prevailing environment [1, 9, 14].

Physiological adaptation in the simplest term is any functional, structural, or molecular change that occurs in an individual as a result of exposure to changing conditions in the environment.

Acclimatization

Other than adaptation, acclimatization has an emphasis on changes and environmental exposures that occur over a limited duration, often on a day-to-day basis. Thus, acclimatization commonly comprises the following definitions: it is the process of adjustments that occur where the application of constant environmental stress results in a diminished physiological strain; acclimatization is a regulatory mechanism, which creates the ability to perform tasks without distress, while adjustments ameliorate the physiological strain experienced on the initial exposure.

Acclimatization can be summarized as the development of protective mechanisms for a state that is compatible with satisfactory physiological operability over a relative short period of time, and not considering any permanent changes to physiological functionality or structure [15].

1.2.4 Physiological System Parameter

Physiological system parameters constitute the gateway to measure and assess physiological systems and also to quantify adaptational changes and mechanisms. The most interesting parameters, involved in homeostatic regulation and maintenance, are the cardiovascular, respiratory, cerebral, neural, and renal-hormonal systems.

Each of these physiological systems incorporates a set of parameters. The parameters describe functionality and structural work of its system. Using these parameters and observing their changes, the functional reaction of the physiological system can be assessed. A few conceptual examples are briefly presented in Table 1.1 and further explored in detail in the following chapters.

Table 1.1 General examples of human adaptation to one or multiple extreme environments. An extreme environment acts as a stressor, based on the prevailing physical quantities. These quantities distort one or multiple biological systems. Any distortion can be quantified using physiological parameters, which also serve to assess adaptational processes

Environment/Physical quantity	Biological system	Physiological parameter	Adaptational process
Underwater/Ambient pressure	Circulatory system	Heart rate, stroke volume, peripheral vasoconstriction	Conservation of oxygen, blood volume shift to body centre
Space/microgravity	Circulatory system	Heart rate, stroke volume, peripheral vasodilation	Blood volume shift to body centre, increased diuresis
	Musculo-skeletal	Muscle density and force	Degeneration of muscle performance
High altitude	Respiratory system	Respiration rate, oxygen saturation	Hyperventilation, haematological, and cardiovascular adjustments
Elite sports competition	Cognitive, mental system	Mental perception, cardiovascular parameters	Training and simulation procedures

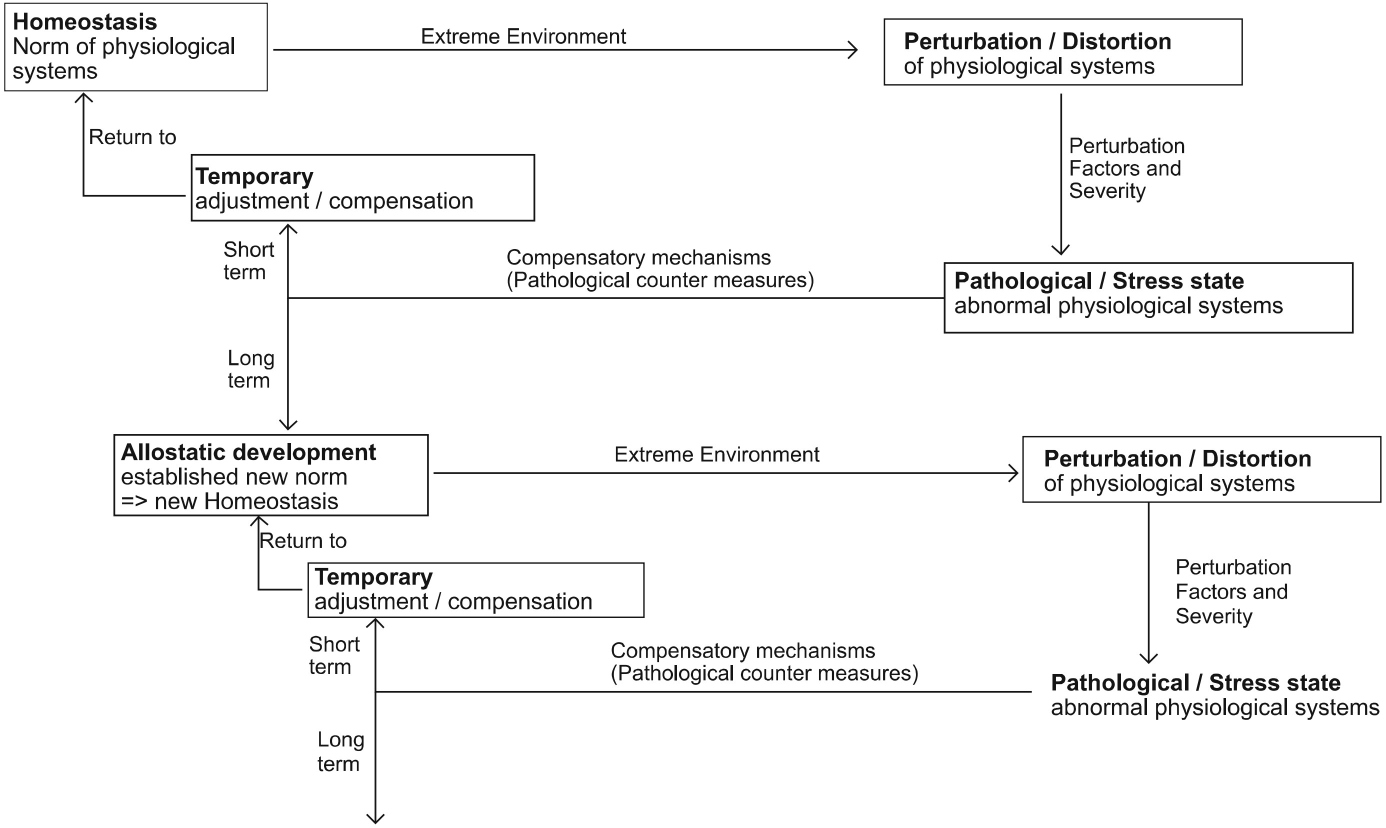

Fig. 1.2 Schematic cycle of physiological adaptation processes that are induced by stressors impacting homeostasis

1.2.5 Response Cycle

Considering the mechanics of homeostasis and allostasis in combination with the effects of adaptation and acclimatization, it becomes clear that there is a continuous dynamic exchange with the physical world. Being alive requires being able to adjust to external stressors. If changes in environmental conditions occur, homeostasis will be disrupted [13]. However, if these changes exceed certain limits where the regulatory compensation is no longer able to reinstate and maintain homeostasis, the life of an organisms is endangered, and death might be inevitable, if no allostatic process is implemented [1].

An adaptational cycle, derived from the concepts described in the academic literature, can be considered as presented in Fig. 1.2. The starting point is the homeostasis of a human internal milieu. Each physiological system is optimized towards the prevailing environmental conditions. Once these conditions change, e.g. exposure to an extreme environment occurs, homeostasis will be disturbed. The new ambient conditions induce a perturbation of one or multiple physiological systems. Physiological distortions are thereby determined by the number of different perturbations, the duration, and severity of the environmental properties that have been altered. At this stage, the physiological systems are in a state of stress and initiate adaptive mechanisms to compensate the distortions. If compensation falls short, pathology can occur in the form of injuries or diseases. However, if the compensatory mechanisms are successfully applied, the next dependence is determined by the duration of the exposure. In short-term exposures the compensatory mechanisms are expected to reinstate a return to the previous homeostasis level. If environmental conditions are changed over a longer period, or be changed permanently and the compensatory mechanisms are not overburdened, it is anticipated that an allostatic development of the physiological systems occurs. Allostatic mechanisms will subsequently establish a new base level that will take over as a new homeostasis level. An individual is now considered to be able to mentally and physically lead a normal life. From here on, the cycle would start all over again.

1.3 Psychological Environment in Humans

Psychological characteristics have been explored independently and sometimes combined with physiology. Adaptation to extremes is an integrative matter that the body and the brain have to solve conjointly. A strong mental state, good anticipation and preparation, as well as the ability to cope with unpredicted occurrences are of significant importance for successful exposure to extreme environments. Research has shown that there is a close interplay between psychology and physiology in humans [16, 17]. One acts on another.

Through the concept of allostasis, the brain is seen as the designated organ responsible for predicting and initiating internal responses to environmental stressors, both in physical and mental nature. Physiological parameters can be utilized to understand how decision making, spatial cognition, emotional aspects, and cortical sensory integration supporting bodily perception and orientation are influenced by and during extreme environment exposure, including both short and prolonged exposure [18].

1.3.1 Resilience

In the scope of extreme environments, psychological resilience can be defined as the ability to "rebound" from adversity, resulting from both physical and mental stressors, when an organism's ability to function has been impaired [16]. In the public health domain, mental assessment and well-being is commonly attributed to the term "wellness". Although sometimes overlapping, the concepts "wellness" and "resilience" are distinguished in this book, with a predominant focus on resilience as the psychological indicator for stress compensation and long-term adjustments regarding mental states.

In first instance, it is generally the sensory nervous system that perceives and interprets external environmental stimuli, classifies them as potentially stressful, and initiates behavioural and physiological responses against the stress stimuli. It is important to note that every individual's adaptation response has the potential to be different based on the environments they are or have been exposed to previously and the length of time for those exposures. For example, those with prior exposure to extreme cold conditions on a regular basis who have not regularly experienced extreme heat will have a greater stress response to extreme heat than those regularly exposed to it and vice versa [1].

The nature of stress stimuli and physiological system distortion can be memorized and stored. Physiologically, the human body can promote the memory of events and situations that in the future may be dangerous using hormonal regulations. This is an adaptive function and in the scope of psychological adjustment commonly referred to as "building up resilience" or "becoming resilient".

In the brain, strong emotions frequently lead to "deja vú" memories, e.g. where we were and what we were doing when we heard about devastating natural or manmade disasters, or remembering the location and event associated with a very positive life experience, such as proposing marriage or receiving a promotion or award [7].

It is widely held that depression, and associated cognitive impairment, as it manifests in humans, may be the result of an inability to return to normal functioning following a stressful or distressing psychological or physical situations, and as such may be an example of lack of resilience (Fig. 1.3).

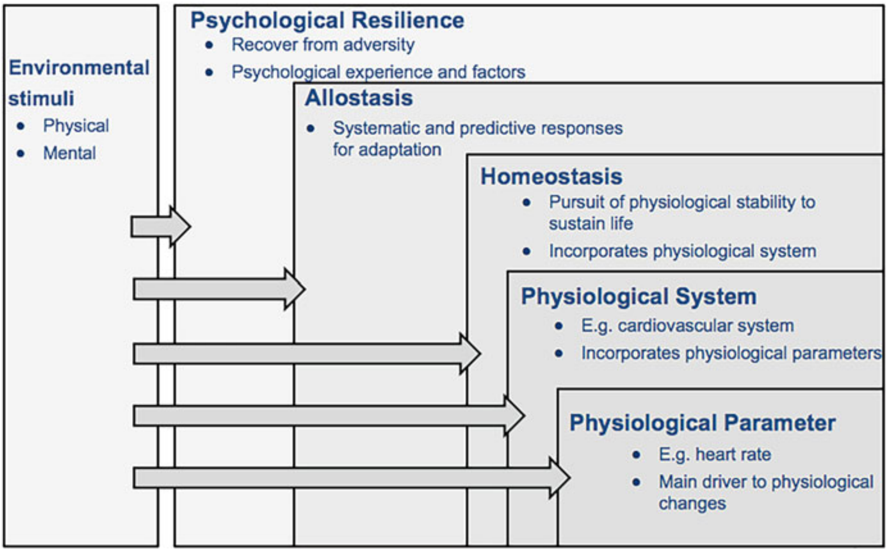

Fig. 1.3 Conceptual overview of the physiology and psychology system in humans. Multiple levels and interaction of the defined systems. Environmental stimuli can affect each system on each level. A combined response including all systems is considered as the best strategy for adaptation and survival

1.4 Coping with Extreme Environments

In biology, adaptation is defined as the extent to which an organism can occupy an environment, use available resources, and reproduce.

Any response designed to allow an organism or a species to survive represents a form of adaptation. Thereby, adaptation can be distinguished into physiological and genetic adaptation.

Physiological adaptation in the simplest terms are any functional, structural, or molecular changes that occur in an individual as a result of exposure to changing conditions in the environment. This simple definition avoids categorizing adaptation by intensity, rate of onset, duration, and sequence of responses.

Studying humans in a range of health states at extremes could help to understand physiological and psychological responses for health and wellness resilience and adaptation on an individualized level across diverse populations [19]. For example, patients with impaired physiological capacities coping without normal environment (which to them becomes extreme), or to better understand the physiology and psychology of the elderly, or to better prepare people working in extreme environments [18].

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Chapter 2
Wearable Technology in Extreme Environments

Brian A. Telfer, Thomas F. Quatieri, Hrishikesh M. Rao, and Jeffrey S. Palmer

2.1 Introduction

Literally hundreds of types of wearable devices have been marketed to consumers over the past ten years, and even to their pets. Wrist-worn devices have been the most popular, but wear positions span the body, integrated in many ways, including sensing embedded in finger rings, arm- and head-bands, earphones, eyeglasses, chest straps and compression shirts, eyeglasses, and leg sleeves. The predominant information provided to consumers relates to heart rate (including resting heart rate), activity (e.g., step count), and sleep (e.g., total sleep time, sleep efficiency). Wearable devices are in high demand; global shipments reached a record of 84.5 million units in the third quarter of 2019 [1], largely driven by consumers who find these wearables valuable to provide motivation for improving health and sleep.

The use of wearable technology is also growing for more specialized domains, such as rehabilitation, monitoring senior populations (particularly for falls), and monitoring athletes. For monitoring of heart health, small devices mounted on body with adhesive patches are replacing cumbersome Holter monitors, and even smartwatches have been adding capabilities to detect heart irregularities [2].

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There is another important, less publicized need for wearable technology, for people who need to remain safe and maximize performance while performing in extreme environments. Examples include:

- Medical providers wearing protective equipment while caring for sick patients, which has been a significant and highly appreciated need during the current COVID-19 pandemic [3] but which has also been a need for other recent infectious disease outbreaks such as Ebola
- People such as fire fighters, biological and chemical hazard first responders, certain maintenance workers, and military service members who need to operate in hot, sweaty, dirty, and potentially toxic conditions, while wearing heavy, partially, or fully encapsulating protective equipment
- Astronauts subject to the unique, isolating dangers of long-duration spaceflight
- Pilots subject to extremes of high-gravity maneuvers and cockpit conditions that may result in physiological episodes [4]
- Elite athletes who are at the edge of physiological and cognitive performance limits
- Professional and recreational divers subject to physiological risks from the underwater environment

Many of these particular applications are the focus of other chapters in this book.

Consumer-grade wearable technology is for the most part unacceptable for these extreme environments. That is because the wearable technology needs to be actionable, accurate, acceptable, integratable, and affordable. These requirements are considered in turn.

First, actionable information is needed that is specific to particular occupations and particular environments. Knowing a team member's heart rate or step count is not information with which a team leader can take action to keep someone safe. On the other hand, knowing that a team member is in danger of experiencing heat stroke within the next 15 minutes allows that person to find a location to remove protective equipment, rest, cool down, and avoid injury. The actionable information needs to be scientifically validated to be accurate. Proprietary measures provided by certain commercial products are unacceptable because the limitations and accuracy are undisclosed. The actionable information also needs to be individualized, because physiological and cognitive capabilities and limitations vary widely across individuals.

Second, accuracy applies to the actionable information, needing not only a probability of detection that is sufficiently high for a particular use case but also a probability of false alarm that is acceptably low to users. Either a probability of detection that is too low or a probability of false alarm that is too high will prevent users from adopting the system due to a lack of trust and/or mission disruption. However, accuracy requirements propagate from the actionable information back to the accuracy of the data analytics and to the accuracy of the sensor measurements. Maintaining accurate sensor accuracy is challenging in extreme environments particularly due to motion artifacts. Motion mitigation algorithms are particularly needed to maintain accuracy.

Third, wearable technology needs to be acceptable to users, or the users will not wear the devices. The technology needs to be comfortable or at least tolerable when worn in hot, dirty, sweaty conditions, and when worn along with protective equipment. The needs to require minimal care by the user, or "wear and forget." In practice, this means that the technology needs to either be integrated in a device that the user already wears, such as a smart watch, a helmet, or ear protection, or that the device have a long battery life (to avoid frequent recharging) and be vanishingly small.

Fourth, the technology must be integratable and upgradable. The devices must be able to integrate with a user's existing equipment, including other sensors, and the user's existing communications (e.g., radio, cell phone, WiFi). Consumer technology is typically vertically integrated from a particular device form factor to sensing to analytics to phone apps and data warehousing by a single company in a proprietary way that does not allow the needed integration with other organizations' sensing, analytics, or equipment. Open architectures are needed to provide well-defined interfaces and modularity. Integrating with existing communications is challenging. Security is an important aspect of integration for many users in extreme environments and has resulted in problems in the past [5]. Security considerations range from short-range communications, where the ubiquitous Bluetooth is not acceptable for certain environments, to hosting data on the cloud, where data must be protected for operational reasons and to protect personal health information. Another important integration aspect is the ability to support team operations. Many people operating in extreme environments operate in teams, which can be in the hundreds. The need for device configuration, charging, data downloading, and team-oriented user interfaces is enabled by an open architecture.

On the additional dimension of affordability, this specialized wearable technology is more expensive than consumer-grade technology because of the smaller market sizes and more sophisticated devices. However, the technology must still be affordable. In some cases, the key technology may be in the form of an algorithm to produce actionable information from a consumer-grade device, in which case a commercial device could be upgraded through software. That would be an ideal option from the affordability standpoint, although it would not by itself address the need to be integratable and upgradeable. An important aspect of affordability is life-cycle cost and logistical burden. For example, having to purchase individually sized device straps, or having to replace these often, e.g., single-use adhesive patches or straps that lose accuracy after laundering, are issues that have arisen.

Meeting all of these constraints is quite challenging.

Examples of important needs for wearable technology in extreme environments are shown in the left column of Fig. 2.1. All of these categories (except for performance enhancement) relate to providing early detection of performance degradation, in order to allow actions to be taken to prevent further degradation and injury. Predictive analytics are needed to map sensor measurements to actionable information. The design of a wearable system to address a particular need flows from left to right in the figure, that is, starting from the actionable information and working back to define the predictive analytics in the form of a physiological or

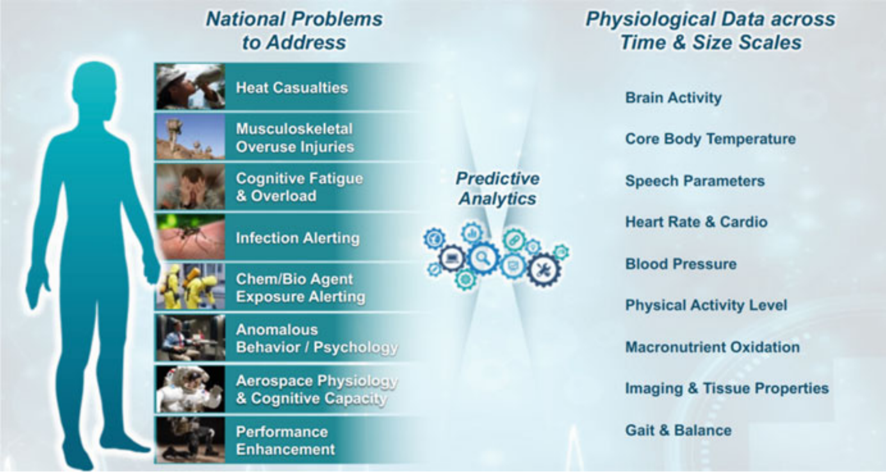


Fig. 2.1 Integrated biomedical sensing required for health and performance in extreme environments

cognitive model and then further back to define the sensor measurements that are needed as inputs to the model, based on physiological data across time and size scales. Systems are being developed to address all of these needs, at various states of development. Examples of recent monitoring progress include:

- Heat injury [6]
- Musculoskeletal injury [7–11]
- Metabolic state [12]
- Cognitive fatigue, overload, and psychological state [13, 14]
- Infection and toxic exposure alerting [15, 16]
- Hearing injury [17]
- High-altitude effects [18]

This chapter highlights early detection of heat injury and assessing cognitive workload as examples of physiological and cognitive monitoring. In addition, eye tracking is considered as an illustrative sensing modality that can support both physiological and cognitive monitoring.

As another example application, musculoskeletal injuries are an under-recognized problem, with hundreds of thousands of injuries reported every year [7]. These injuries may be acute or chronic. There is the potential to provide early detection of lower-limb overuse injuries, such as stress fractures, by using wearable accelerometers to detect subtle changes in gait and gait symmetry [9]. Evaluation of equipment is also an important consideration for avoiding musculoskeletal injuries, since workers in extreme environments often carry heavy loads. Thus, it is important to evaluate how particular equipment options affect how people carry the loads and how agility is affected. Wearable technology that has been applied for these types of evaluations includes inertial measurement units (IMUs: combined accelerometer, gyrometer, and magnetometer) [8, 10] and custom load-sensing shoe inserts [11]. IMUs provide a rich source of information on body position and movement, especially when worn at multiple body positions, but their relatively high-power consumption makes them best suited for short-term monitoring as opposed to long-term operations. For long-term operations, accelerometers consume significantly less power. There are several commercial sources for load-sensing shoe inserts that are intended for monitoring over the course of a few hours in a laboratory. The challenge for these sensors is to maintain calibration over longer periods, e.g., days, while being durable and low cost. The state of the art is based on strain gauges embedded in a shoe insert [11]. It has the potential to maintain calibration for days of wear, but would cost more than 1000 USD, so is currently better suited to small-scale equipment evaluations rather than large-scale deployment.

2.2 Physiological Monitoring Example: Heat Injury

Heat injury monitoring is an example of one of the more mature physiological monitoring capabilities in extreme environments. Heat stroke, the most serious form of heat injury, can result in death or permanent disability. Heat injuries are also recognized as a leading cause of death and disability in US high school and college athletes, and more broadly, 5946 people have been treated in US emergency departments each year for heat injuries during athletic or recreational activities [19]. Outside of the USA, hundreds of construction workers are dying each year in Qatar alone [20]. The number of exertional heat strokes among US active-duty service members almost doubled between 2008 and 2018, with 578 reported cases in 2018 [21]. The seriousness of the problem in the military is highlighted in [22, 23].

A method to predict and avoid heat injuries is clearly needed. Wet bulb globe temperature and related indices based on ambient temperature and humidity are used to assess group-average risk of heat injury [24], but because of significant variations in human physiology, these indices are inadequate to predict an individual's heat injury risk. Insight into an individual's physiological state can be gained through monitoring the rise of core body temperature because one of the main signs of heat stroke is considered to be a core body temperature of 104 °F or above. However, the gold standard methods for measuring core body temperature—rectal probes or ingestible sensors—are not acceptable or practical for routine use. In addition, high core body temperature does not always lead to heat stroke; for example, well-trained runners have been seen to reach and maintain 104 °F with no ill effects in cool ambient temperatures [25]. Heat injuries can also occur at lower core body temperature [26] (e.g., in individuals who are not heat acclimatized or who have preexisting health conditions).

To prototype a solution, MIT Lincoln Laboratory and the US Army prototyped and tested the Open Body Area Network (OBAN) Physiological Status Monitor (PSM) and transitioned the technology to Odic, Inc. (Littleton MA, USA) [6]. The purpose is to predict if an individual is at risk of heat injury within the next few

Fig. 2.2 Wearable portion of OBAN PSM system

minutes. That lead time can be sufficient to allow a person to stop activity, cool down, and avoid injury. The wearable device is worn on a commercial chest strap, as shown in Fig. 2.2.

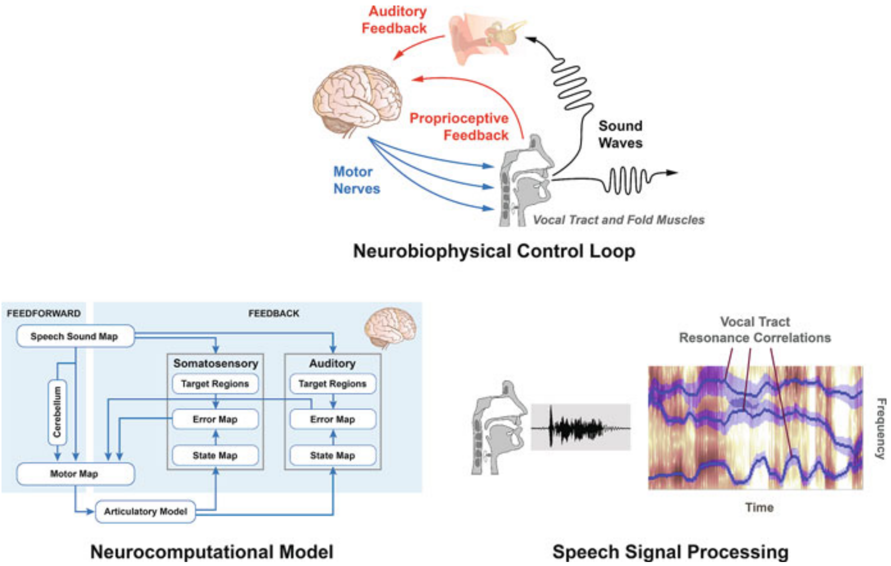
As its name highlights, the OBAN PSM is built on a government-owned, open communication specification that allows multiple wearable systems to be integrated, avoiding proprietary, stove-piped devices. The system includes three components: a sensor puck that is worn on a chest strap, a phone app that receives and displays team members' status, and a docking station that configures, recharges, and downloads data from the pucks. To predict heat injuries, the OBAN PSM puck senses heart rate, accelerometry, and skin temperature. From these sensors, the puck estimates core body temperature by using a validated algorithm developed by the US Army Research Institute of Environmental Medicine [27, 28] and a neuromotor incoordination index [29] that reflects a decrease in coordination often observed with impending heat injuries. The system has been tested with more than 2000 volunteers over the past two years, with nearly perfect detection accuracy and a false alarm rate of 10% or less, based on post hoc analysis. The false alarm rate has been reduced by about a factor of 4 from methods that were previously the state of the art.

This particular application is sufficiently mature to serve as an example of desirable attributes for a wearable system for extreme environments: actionable, accurate, acceptable, integratable, and affordable. The system is actionable because it alerts a training instructor to check on a particular individual who is at risk of heat injury in the next few minutes, allowing the instructor to have the individual cool down through rest or active cooling. The system is accurate, yielding nearly perfect detection accuracy and a false alarm rate of 10% or less, based on post hoc analysis. The false alarm rate has been reduced by about a factor of four from methods that were previously the state of the art. Earlier testing had determined that wrist-worn optical sensing of heart rate was not sufficiently accurate to support the core temperature estimation algorithm [6, 30], which resulted in OBAN PSM using the mature, accurate electrical sensing of heart rate from a commercial chest strap. The system acceptability to users is basically the same as for any monitor requiring a chest strap. During periods of physical activity, users are generally not aware of the system, although after wearing for hours of high activity, a few users have experienced skin irritation from chafing. In addition, a few users have found that the chest strap slips down the torso, which would require a shoulder strap to address. (Finding more acceptable wear locations that can meet heart rate accuracy requirements is an ongoing effort. For example, optical heart sensing on the upper arm currently appears to be accurate [31–33] as well as more acceptable to some users.) The one-week battery life also increases acceptability, by not requiring the users to recharge the device daily. The system is integratable, being designed to communicate by Bluetooth (as well as an alternative operationally acceptable radio) to a smartphone app or long-range relay, making use of the OBAN messaging specification. The system also is designed to operate with hundreds of users simultaneously, using charging stations that accommodate 50 or more wearable pucks and configuration and download software that is designed to manage hundreds of devices. Integration has required significant effort through multiple iterations of testing with users. To increase affordability, the system uses a commercial chest strap supplied by multiple vendors at a cost of less than $ 100 US. A custom-designed chest strap might have increased acceptability but at a greatly increased cost. When manufactured in volume, it is anticipated that wearable puck could cost about the same as a commercial heart rate sensor, about $ 500 US. Currently, about 1000 of the devices have been produced. It should be clear from this example application that there are tradeoffs involved in meeting the desirable attributes, which is true for any wearable technology for extreme environments.

2.3 Cognitive Monitoring Example: Cognitive Workload

Just as it is important to monitor physiological health during operational stressors, it is important to monitor cognitive health and performance. Many noninvasive, wearable sensing modalities are available to monitor cognitive status, including speech and facial muscle coordination, gait, fine and gross coordination of the extremities, eye tracking, pupillometry, electrodermal activity, and interactions with the environment, such as how a user interacts with a smartphone or cockpit controls. All of these modalities are indirect measures of cognition that measure how the brain controls functions external to the brain. Progress has also been made on wearable electroencephalography (EEG) that directly measures brain electrical activity, but this technology is currently best suited to sedentary users.

Speech and facial muscle coordination in particular provide a window on the function of many parts of the brain [13]. Both are highly complex behaviors that


Neurobiophysical Control Loop

Neurocomputational Model

Speech Signal Processing

Fig. 2.3 Neurobiophysical model of auditory and speech pathways as a basis for features for cognitive monitoring

require precise coordination across different regions of the brain. For example, to generate speech, one's brain must first form a concept to express, translate the concept to sentences and words, then to syllables and phonemes and their phonetic representations: position, state of articulators (vocal folds), timing and coordination of articulators and vocal folds, neural signaling and muscle activation, and speech out. Auditory and somatosensory feedback mechanisms are used to monitor and self-correct speech production. Somatosensory components include proprioception (person's sense of tongue placement and vocal cord vibration) and tactile feedback (sense of tongue placement and vocal cord vibration). Figure 2.3 illustrates the neurocomputational speech production model [34], which includes articulatory feedforward mechanisms and auditory and somatosensory feedback errors [13, 35]. This model serves as a foundation to motivate the extraction from audio acoustic features that represent the timing and coordination of underlying mechanism [36, 37]. Although not described here, the model's optimal parameter fit, given a measured speech signal, can itself also provide model features by using correlation structure analysis [38].

A particular application focus is to monitor cognitive load, which is the demand placed on cognitive resources that is required by a particular set of tasks. Some tasks require a greater cognitive load than others, and long periods of sustained activity or attention expend cognitive resources over time and lead to fatigue. An individual's ability to manage a particular cognitive load will be degraded by stress from extreme environments as well as the individual's internal state, e.g., emotional state, nutritional status, lack of sleep. In operational environments, the

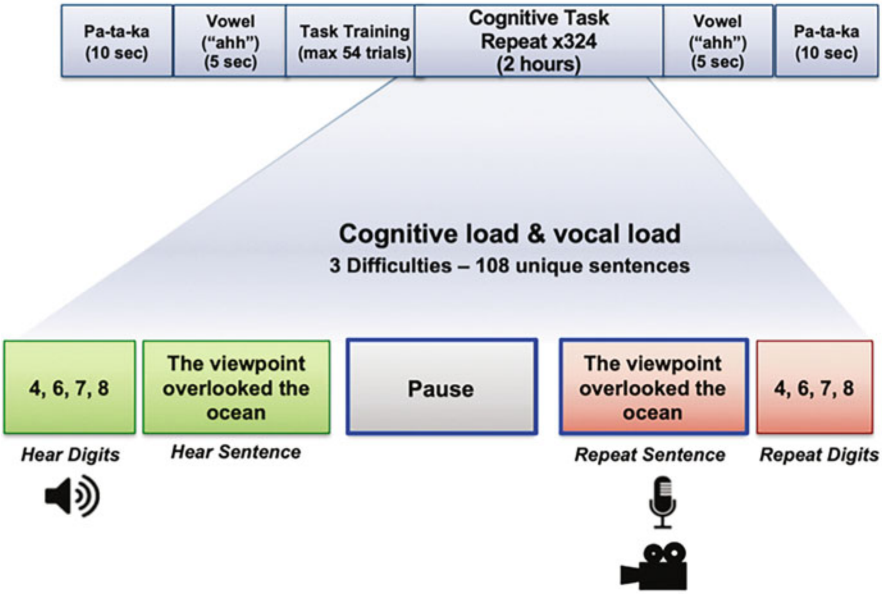


Fig. 2.4 Cognitive load protocol was used to collect data from 11 human subjects

goal is typically to assess cognitive ability and readiness. Monitoring speech is well suited for assessing cognitive load, since speech and cognitive processes are highly coupled in the brain, sharing common pathways and processes.

In one example of assessing cognitive load in a working memory protocol, 11 human subjects listened to a sequence of digits followed by a sentence [13, 37]. After a pause, the subject repeated the sentence and the digits. In different trials, the working memory load was modified by varying the number of digits. EEG (64 channel) was measured during the pause to avoid motion artifacts. Features were also extracted from speech and facial video when the sentence was repeated. Prior to and after the two-hour cognitive task, the subjects recited the diadochokinetic sequence "pa-ta-ka" and the vowel "ahh" that are standards for analyzing speech pre- and post-fatigue. This protocol is illustrated in Fig. 2.4.

The data were organized in two categories of cognitive load: low (2–5 digits) and high (4–7 digits). The ability to distinguish between the two categories using correlation structure analysis was quantified with receiver operating characteristics for three sets of sensing modalities: (1) EEG, (2) audio, and video, and (3) EEG, audio, and video. Performance was also assessed for fusing across different numbers of trials. The results are shown in Fig. 2.5. Fusing across multiple trials improves performance in all cases, with the best results using 60 trials of 6 minutes duration. The best results are obtained by fusing EEG, audio, and video, with the performance of audio and video alone approaching that of 64-channel EEG.

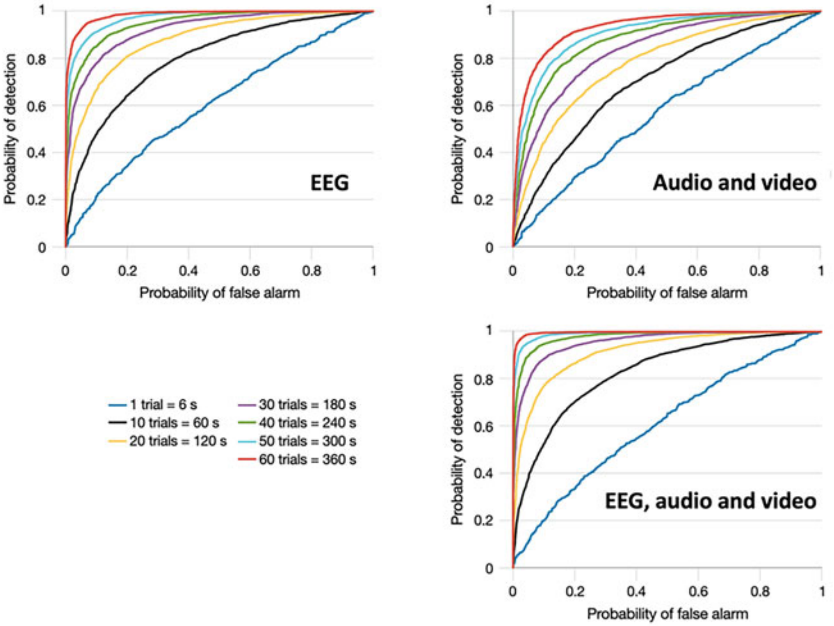


Fig. 2.5 Receiver operating characteristics for detecting cognitive load based on sensory modality [13]

In addition to yielding promising results for monitoring cognitive load, these methods have shown promise for assessing a variety of conditions related to brain health, such as depression, which is relevant for the need to monitor mental health during long duration spaceflight [13]. These results are significant, but much research needs to be done before this technology can be operationalized. The current research focuses on detecting high cognitive workload, which could be actionable by alerting people that they need to rest or rebalance the workload among their team members. More recent research in collaboration with the US Army Research Institute of Environment Medicine addresses more operationally relevant cognitive batteries and their effect on cognitive fatigue and performance, as well as cognitive load [39]. The research focuses on sensing modalities that could be acceptable in extreme environments, particularly speech.

2.4 Sensing Modality Example: Eye Tracking

Eye tracking is considered as an important sensor modality that will be important for both physiological and cognitive applications by measuring eye movements, tracking changes in pupil size (pupillometry) [40], and measuring eye closures or blinks [41]. Of these, the latter category of measurements has been long studied to monitor driver fatigue [42].

Considering long duration spaceflight as a particular example for extreme environments, eye tracking has important applications to monitoring: visual impairment, sleep quality and alertness assessment, and microgravity (de-)adaptation.

Visual impairment from spaceflight-associated neuro-ocular syndrome (SANS) [43] is a problem unique to living in space for long periods that affects the globe of the eye, optic nerve, and intracranial pressure levels [44]. The US National Aeronautics and Space Administration (NASA) considers SANS as a high likelihood, high consequence condition. According to NASA's 2018 Strategic Plan 2018: "Human research conducted on the ISS and future low Earth orbit platforms will help mitigate the health risks anticipated on exploration missions, such as visual impairment and intracranial pressure." Eye tracking may contribute to monitoring SANS during spaceflight by providing mechanism-based insight into the onset of intracranial pressure. Astronauts also suffer from more frequent sleep loss, circadian desynchrony, and sleep inertia than during spaceflight. This leads to decreased performance and fitness for duty during spaceflight. Continuous eye tracking provides one modality for assessing sleep quality and wakeful alertness. Of course, sleep monitoring with wearables is a large and growing research area and consumer market as well [45, 46] and is not surveyed in this chapter. As an additional need for spaceflight monitoring, vestibular reorientation occurs upon microgravity onset and offset. Eye movements, influenced by vestibular-ocular coordination, could serve as an indicator of an individual's adaptation [47].

A particular consideration for eye monitoring is acceptability. In commercial systems, eye movement is typically monitored by remote cameras, which is well suited to monitor seated operators, e.g., drivers or computer analysts, but is not well suited to monitoring ambulatory people in extreme conditions. An alternative is to integrate cameras and illuminators into eyeglasses. Example products include the Tobii Pro Glasses (Stockholm, Sweden) and Microsoft HoloLens (Redmond, Washington USA). Another alternative with a smaller form factor is to measure ocular features using electrooculography (EOG) with wearable adhesive electrodes positioned at the sides of eyes. An example comparison of video and EOG eye tracking in Fig. 2.6 illustrates that EOG may be a viable option.

2.5 Summary

People who need to work in extreme environments are not always at the forefront of our minds. Astronauts who spend months in space are far away, and toxic accidents that require specialized response teams are fortunately relatively infrequent. However, many of us have recently witnessed COVID-19 responders in our neighborhoods or in the hospital. Many of us increasingly witness fire fighters working to control overwhelming infernos. Each of these emergencies require

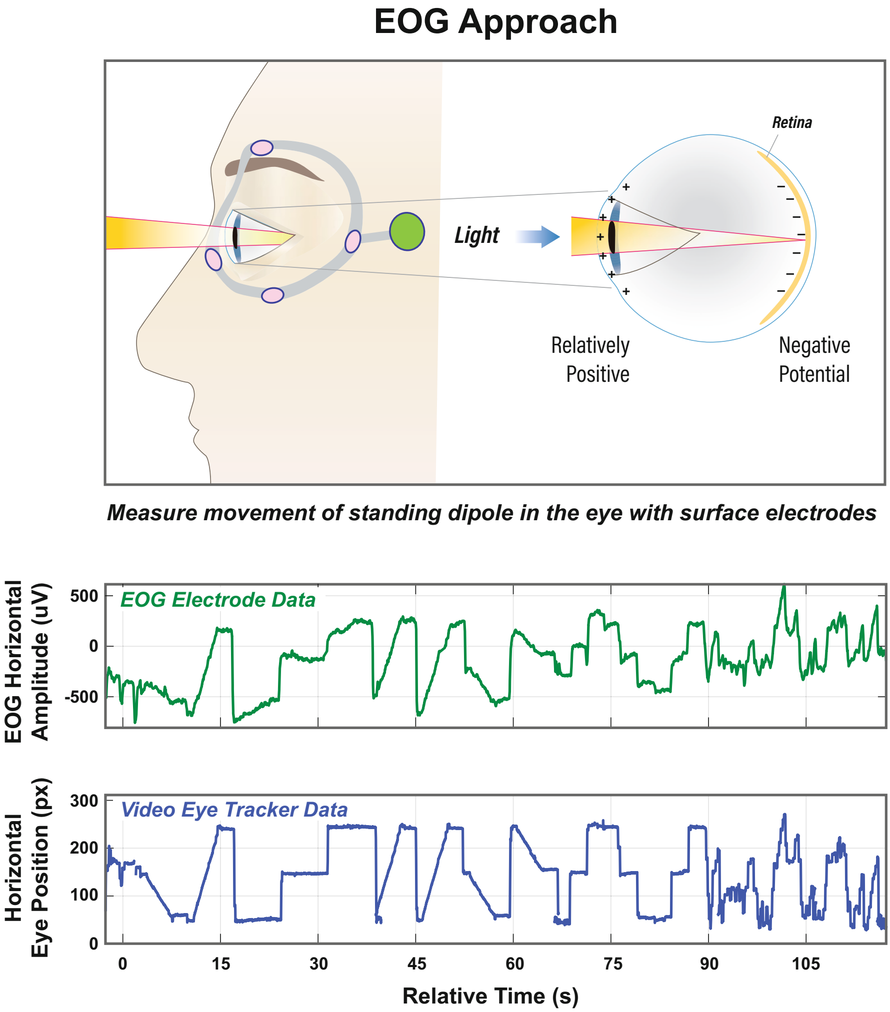


Fig. 2.6 Comparison of eye movements when collected simultaneously using electrooculography (EOG) and video eye tracking system

specialized encapsulating protective gear to operate in an extreme environment and pose special physical and cognitive demands on responders. The need to help these responders monitor their physical and cognitive function has never been greater.

Developing wearable technology for extreme environments is difficult because it needs to be actionable, accurate, acceptable, integratable, and affordable. Technology that meets only one or two of these needs will not be accepted by the users. Iterative testing with users is essential. As an example of physiological monitoring, a system for early detection of heat injury has undergone several iterations with users, with these five needs being increasingly met after each iteration. As more and more users try out the monitors, more data are collected, which are used to further improve the accuracy. The current focus is on improving the integration of individual monitors with status displays that may be several kilometers away, in areas without cell coverage. For cognitive monitoring, early detection of cognitive overload and brain health issues is showing promising results in the laboratory with sensing modalities such as speech that could be accepted operationally, but considerable work remains to transition the technology to the field, in a way that provides actionable information to the user. Eye monitoring technology, which provides another window on both physiological and cognitive function, is advancing relatively quickly in both the commercial and research domains.

This is an exciting and vital time to contribute to wearable technology for extreme environments. The need will only increase in coming decades, on Earth as well as in space. Protecting workers who must work in unlivable heat from climate change will become critical. In addition, long duration spaceflights, e.g., potential flights to Mars, pose formidable challenges to physical and mental health.

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Chapter 3
Frameworks and Platforms for Extreme Environments Adaptation and Resilience Monitoring

Carolyn McGregor AM and Tobias Cibis

3.1 Introduction

Extreme environments can cause a number of in the moment and long-term physiological and psychological changes, as a compensatory or long-term adaptation response, the extent of which depends on the degree of resilience and acclimation that has been developed for the extreme environment and/or specific context within a given deployment, mission or operation. To enable the systemic assessment of the physiological health and psychological wellness of humans in extreme environments, together with their degree of adaptation and resilience responses, robust and reliable computing platforms are required that are instantiations of information systems frameworks designed to meet the needs of extreme environment health, wellness, resilience and adaptation monitoring.

This chapter provides an overview of sensing devices, computing systems and platforms along with the information systems frameworks within the context of extreme environments from a generic perspective. These concepts are further

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explored within the chapters of this book to provide further details for specific extreme natural environments such as space and diving along with extreme working environments such as tactical operations, firefighting and elite sport. A brief history of these sensing devices and computing systems that laid the foundation for extreme environment monitoring is presented. This is followed by a brief history of the representation of these devices and systems logically within information systems frameworks. The concept of continuous health monitoring as a form of digital twin platform is introduced. An information systems framework for extreme environment health, wellness, resilience and adaptation monitoring is then introduced. Trends in current sensing devices, computing systems and platforms are detailed as an introduction to themes that will be detailed further within the remaining chapters of this book.

Within this chapter concepts from biomedical, electrical and computer engineering, computer science, information systems, decision support, health informatics and clinical decision support theory are presented. Decision support systems (DSS) and clinical decision support systems (CDSS) are instantiations of decision support and clinical decision support information systems frameworks, respectively. Within this chapter, we propose that health and wellness monitoring is a form of clinical decision support system from the perspective of the computer science foundations that can be drawn from. As a result of this interdisciplinary approach, a note on terminology is required. Within the electrical and computer engineering domain, sensor devices acquire data from the object(s) they are sensing. From a decision support and clinical decision support perspective, those sensor devices are perceived as the devices that collect the data. To enable the DSS or CDSS to turn that data into information, knowledge and wisdom it must first acquire the data from the sensor device. As a result, in this chapter, the term Data Collection is used to describe the process of the sensor device to perform its own function to create the data and the term Data Acquisition is used for the Health and Wellness monitoring component to acquire the data from the sensor device.

3.2 A Brief History of Sensing Devices, Information System Frameworks and Computing Platforms for Continuous Health Monitoring

In this section the history of continuous health monitoring is presented through a brief history of the sensing devices and computing systems within this context. This is followed by a brief history of the representation of these devices and systems logically within information systems frameworks.

3.2.1 Early Systems for Continuous Health Monitoring

Arguably, the first wearable computer was designed by Ed Thorp and Claude Shannon from MIT Media Lab for a rather unusual purpose. The wearable computer was intended to be used for cheating in gambling. The gambling in question was Black Jack and the device was programmed to help the player to count cards and beat the bank. The wearable device was the size of a cigarette box and was operated using switches that were attached to the subject's big toe and provided auditory feedback [1]. However, from this infant stage, wearable devices have evolved in all directions and are now common devices in daily life [2].

The first attempts to record the electrical activity of the human heart were performed by Augustus Waller in May 1887 at St. Mary's Hospital, London [3]. However, the quality of the tracings was poor. Willem Einthoven invented the first electrocardiogram (ECG) device in 1895. Subjects put their hands and feet in large buckets of saline acting as electrodes. His three limb lead method is known as Einthoven's triangle. He received the Nobel Prize for his work. His approach went on to become a standardized approach that is still in use today [4].

The first portable ECG monitoring device, the Holter monitor, was invented by Norman Jeffery Holter in late 1940s. The initial apparatus weighed approximately 40 kg and was strapped to his back while riding a bicycle [5]. This device enabled the printing of an ECG onto paper.

In January 1950, Himmelstein and Scheiner recognized the valuable "need for continuous information about cardiac action during surgery" and began using an instrument they called a Cardiotachoscope during surgery. It used a cathode ray tube (CRT) to display ECG and heart rate and was large enough to be read at a distance from the device with connection cables that were 25 ft. An alarm mechanism enabled a low alarm for heart rate to be set between 30–80 beats per minute (bpm) and an upper alarm between 70–200 bpm with the alarm activating a warning light or a sound. A permanent record of the ECG could be created by attaching a direct writing cardiograph to leads on the instruments control panel [6]. As such data analysis performed on the raw data within the sensing device was limited to the derivation to simple metrics such as heart rate.

Human acclimation research dates back to the late 1950s, where investigations of physiological responses during permanent and temporary exposure to cold environments were performed [7]. They demonstrated that repeated exposure to cold environments enables development of adaptation and resilience.

The Russian Institute for Biomedical Problems utilized continuous ECG monitoring when Yuri Gagarin completed the first human journey into outer space on 12th April 1961. The analysis of that ECG was led by Prof. Dr Roman Baevsky, who retrospectively analyzed the distances between the R peaks in the QRS complex of the electrocardiogram collected during that mission using a ruler to measure the distance on the electrocardiogram printout to assess heart rate and heart rate variability throughout the mission [8].

As a result, while the data collection and data visualization components of a health monitoring system were evident in these early systems, visualization of the data collected by medical devices was either in the form of a visual display or printout on paper. Within some medical devices the data collection device was separated from the data visualization. Data collection from medical devices continued to work within the paradigm of generating outputs for printing and evolved to utilizing RS232 serial ports to output data to printers. Many medical devices in use today are still devices that output data via serial communications and devices are still procured that have no mechanism to enable output of data from the device [9].

In 1974, Shortliffe [10], published a technical report for the US Department of Defense that detailed MYCIN, named after the common suffix for several antibiotics, which was a rule-based computer program designed to assist physicians in selecting the appropriate therapy for patients with bacterial infections. This was believed to be one of the first clinical decision support systems [11]. MYCIN introduced a computer modelling layer between the Data Collection layer and the Data visualization later. However, this program was written in Lisp and did not directly ingest patient data, but rather enabled question and answer type of interaction enabling the physician to provide information about the organism detected and in what form of culture, which resulted in the recommendation of an antibiotic.

Right from this early stage of using computer systems to derive meaning from patient data, Shortcliffe et al. [10] noted that "since clinicians are not likely to accept such a system unless they can understand why the recommended therapy has been selected, the system has to do more than give dogmatic advice. It is also important to let the program explain its recommendation when queried and to do so in terms that suggest to the physician that the program approaches problems in much the same way that he does."

3.2.2 Information System Frameworks for Continuous Health Monitoring

The creation of devices such as those introduced in the prior section to generate data gave rise to the need for systems and ultimately multi-component platforms that could make use of the data. Further, it motivated the creation of a theoretical understanding of systemic approaches or frameworks to describe these systems and the processes enabling their use. Specifically, there was a need to establish structured ways to enable the data to be given meaning and context so that it became information and ultimately knowledge. There was a need to describe these systems through Information System Frameworks. In this section we provide a brief background on the evolution of information systems frameworks to support decision making in healthcare and specifically in the area of continuous health monitoring in order to set the scene for our later sections that outline the principles of continuous health monitoring frameworks, platforms and systems that are described within this book. In the 1980s the Data Warehouse architecture was proposed and began to be adopted by many industries to enable the data used in transactional systems to be used to support decision making. In 2002, McGregor noted the information systems theory that had emerged to describe Data Warehouses by Sprague and Watson [12] and Turban [13]. They described the three components of data management for databases to store and manage the data, model management that provide analytics capabilities and user interfaces to access the models and data [14]. In that work, McGregor et al. proposed the e-Baby Data Warehouse architecture that demonstrated the Data Warehouse framework within the context of neonatology. This was arguably the earliest application of the data warehouse information systems framework to healthcare. Specifically, the need to add a Data Collection component was recognized, in addition to the Data Warehouse, the Model Base and User Interface. The goal of the project was improving the clinical decision support for premature and ill term infants through real-time analysis of continuous physiological data streams to support automated reporting and discharge letter generation. As a result, she recognized the need for the Data Collection component to enable continuous data streaming of physiological data, an aspect not seen previously in Data Warehouse frameworks, systems or platforms. In addition, all raw physiological data together with data derived within the modelling component was stored within the Data Warehouse. Interestingly, premature birth can be considered as an extreme environment as some infants are born up to 17 weeks early in the 40 week gestation cycle and have potential for survival. Many vital organs have to continue to develop outside the womb, they have to deal with gravity earlier than planned and their lungs have to take on the role of provisioning oxygen earlier than planned.

In 2008, Kong et al. [11] noted that a three component general framework model could be defined to describe CDSS. They describe a data layer that contains patient data such as clinical signs, symptoms and laboratory results. They noted that the most common form of database used to record patient history data and clinical signs and symptoms was the relational database. They outline a model layer that contains inference mechanism and knowledge based components. The final layer is the diagnostic and therapeutic recommendation layer. However, this framework did not provide a component to store the raw or derived data that was created by the inference mechanism and knowledge based components. As a result, there was no approach for the management of the data used (Fig. 3.1).

Within a broader context, Kimball and Ross defined the traditional data warehouse model, [15] as containing (1) operational source systems generating organizational data and extraction tools required to retrieve source data from these operational systems, (2) Data Staging, also known as the ETL (Extraction, Transformation, Loading) layer to clean and standardize the operational data, (3) Data Marts to store subsets of this data in a standardized way for improved efficiency and speed when querying specialized sets of data and (4) dedicated portals for Data Visualization. However, this traditional data warehouse model was based on

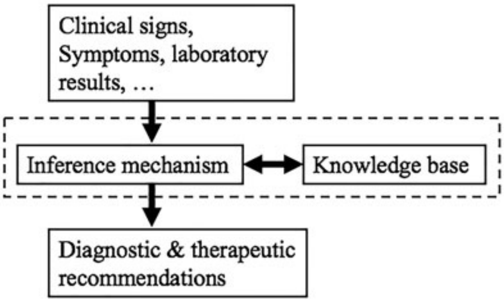

Fig. 3.1 The general framework of CDSS [11]

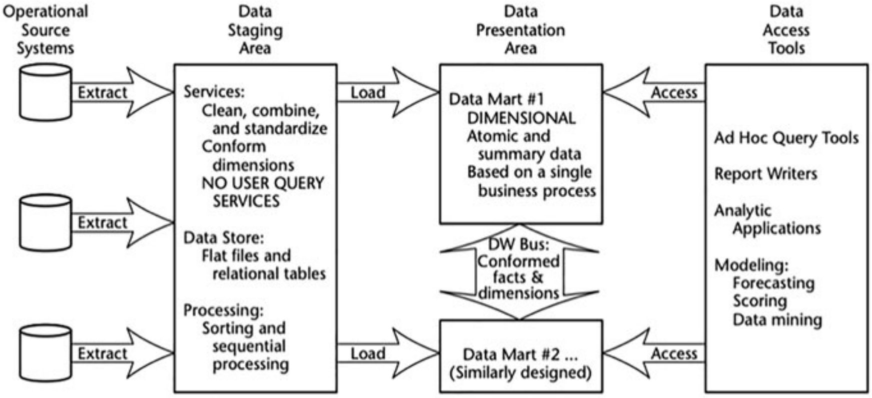

Fig. 3.2 Basic elements of a data warehouse [15]

nightly data extraction, overnight loading of Data Marts and Report Static report preparation for visualization. The scope of the Data Warehouse was sourcing data from operational source systems and not from sensor devices as was proposed in e-Baby (Fig. 3.2).

Big Data has been recognized as a subset of data having the properties of volume, velocity and variety [9]. Real-time health monitoring in extreme environments represents a Big Data challenge due to the volume and frequency (velocity) of data streams from sensor devices and the variety of sensor devices that can be used to gather data from the participants and the environment. Utilizing Big Data requires computing approaches that support the continuous arrival of data such as high speed physiological data streams and consider its temporal nature when deriving information and knowledge from it [9].

One of the earliest Big Data analytics platforms for clinical decision support was the Artemis project led by McGregor. Artemis was created in 2008–2009 through a joint research project between the University of Ontario Institute of Technology and the IBM TJ Watsons Research Center funded by an IBM First-of-a-Kind project.

Demonstrated within the context of neonatal intensive care and with an initial clinical algorithm for the real-time earlier onset detection of late onset neonatal sepsis (LONS), Artemis was initially piloted in the neonatal intensive care unit of The Hospital for Sick Children, Toronto, Canada. This platform contained a Data Acquisition component to acquire data collected by the existing bedside medical devices in the NICU in real-time. It contained an Online Analytics component that utilized the IBM Infosphere Streams stream computing component to ingest and analyze the physiological data in real-time to produce a second by second risk score for LONS [16–18]. In 2011, McGregor proposed a cloud computing framework for real-time rural and remote service of critical care that separated the Data Collection and Data Acquisition components from the remaining components through the provision of a series of web services to enable the interaction with Artemis from a remote location [18]. This was then extended to propose a health analytics as a service (HAaaS) framework containing components for data collection, data acquisition, data buffering and transmission within an edge computing construct at the location where the humans are being monitored. The remote cloud-based HAaaS model contains data transformation through the use of an adaptive application program interface (API), data analytics, data storage and information exploration. Data analytics and information exploration can be provisioned in real-time and retrospectively [19, 20].

In 2018, Wang et al. [21] proposed a big data analytics framework for clinical decision support. That architecture is comprised of five major architectural layers: (1) data layer, (2) data transformation, (3) analytics, (4) information exploration and (5) data governance. However, that architecture does not support the analytics being provided as HAaaS provisioned through the cloud and decoupled from the other components.

While research and development to date have enabled the creation of monitoring approaches to support health and wellness broadly, extreme environments present unique challenges that require those deployed within them to build adaptation and/or resilience to the particular extreme environments in question. In addition, the extreme environment can also create unique challenges for the sensing devices, computing systems and platforms to support them. The next section presents a framework to address this need.

3.3 A Framework for Extreme Environment Health and Wellness Monitoring

This section presents the generalized framework for extreme environment health, wellness, resilience and adaptation monitoring. It extends the prior information systems approaches, specifically those proposed by McGregor for HAaaS in healthcare [20] and space [29] and for resilience and acclimation resilience assessment and development [22, 23]. It is specifically designed for the extreme environment

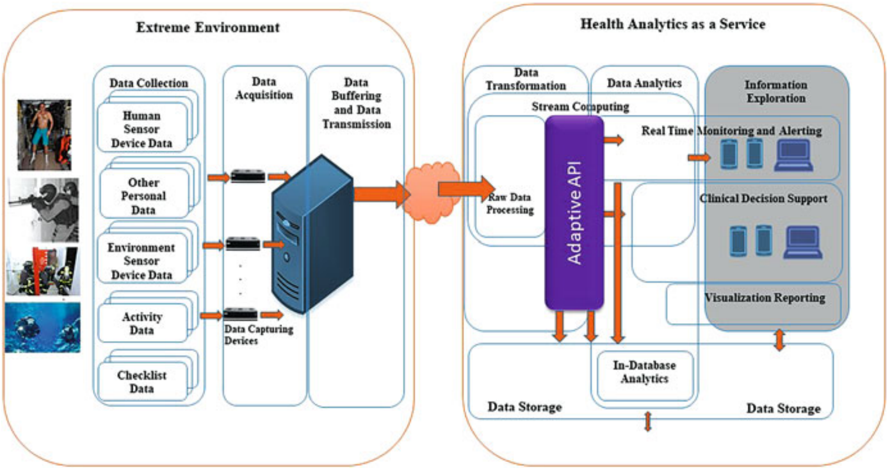

Fig. 3.3 Framework for extreme environment health and wellness monitoring—extended from [20, 22, 23, 29]

context generally. It enables the assessment of the individual to support health monitoring to detect the onset of various conditions. It supports the assessment of wellness for overall mental wellbeing. It enables resilience assessment and development to stressors specific to that extreme environment context and it enables adaptation assessment and development to the environmental factors associated with the extreme environment that can include assessment of the use of counter measure devices where available. Subclasses of data broadly applicable for extreme environments are detailed within the data collection component and resilience and adaptation analytics, visualizations and derived data are contained in the data analytics, information exploration and data storage components.

The framework is presented in Fig. 3.3 and contains components for data collection, data acquisition, data buffering, data transmission, data transformation, data analytics, data storage and information exploration. Connectivity between the Data Transformation and the Data Analytics and Data Storage components is via an adaptive application program interface (API) [19]. Each of these components is outlined further in the following subsections.

While not outlined specifically in the framework, security and privacy are key overarching concepts when the framework is translated into instances of computing systems and platforms and have implications on the implementation of each component within the framework together with the movement of data, information and knowledge from one component to another. They form key guiding principles and requirements throughout the design, development, testing, deployment and post implementation of any computing system or platform.

3.3.1 Extreme Environment Data

As shown in Fig. 3.3, there are broadly five types of extreme environment data namely: human sensor device data, other personal data, environmental sensor device data, activity data and countermeasure data.

Human sensor devices are required to collect physiological data streams. Generally speaking, physiological data creates the gateway to measure and assess physiological systems. Human physiological systems involved in physiological regulation and maintenance in the scope of extreme environment exposure are the cardiovascular, respiratory, cerebral, neural and renal-hormonal systems. Each of these physiological systems incorporates a set of biological parameters. These parameters are monitored with non-invasive technology, thereby describing the functionality and structural work of its system. Using these parameters and observing their changes enables the functional reaction of the physiological system to be assessed. Further details on the forms of impact on these systems is provided in subsequent chapters that present more details on specific extreme environments.

Other personal data provide additional details about the participant and can include biological sex, gender, age, height, weight, race and ethnicity, medical history, climatic exposure to date, caffeine medications and drugs, and sleep patterns. Load carriage information is important for firefighters and technical officers. In addition, checklists and other forms of qualitative assessment can enable the participant to reflect on their own current state of health and wellbeing to provide further relevant contextual information. Subsequent chapters within this book provide more details on the relevance of this data within each extreme environment context.

Environmental sensors collect data about the extreme environment such as temperature, humidity, barometric pressure and amount of light along with the levels of steam, fog or smoke [24]. Sound levels and other sensor stimulating information can be collected also. While completing a mission or operation within an extreme environment, various activities are performed. As a result, activity data is collected to gather details of when each participant within the extreme environment is performing various activities. This provides important contextual information to understand the impact of performing the mission or operation in the extreme environment [22, 23].

Countermeasure data is collected from countermeasure devices and can be used to assess the short- term and long-term impact of the countermeasure activity on the adaptation response in longer duration extreme environment deployments such as space missions [25].

3.3.2 Data Collection

The Data Collection component enables the collection of the five types of data outlined in the previous section for the assessment of the individual and populations in the extreme environment. The collection of data from the individual and environment can present many challenges as a result of the extreme environment, movement, the protective clothing worn by the individual and the tasks they are performing.

The two main collection techniques for physiological information are imaging and sensing. While imaging approaches employ techniques to visualize the inside structures of an organism's body, sensing technologies measure external stimuli and transform them into electric information and subsequently into digital data. Considering the scope of operational application during extreme environment exposure, imaging technology is less suitable. In extreme environment scenarios accurate imaging seems unlikely due to object motion and physical conditions interfering with the measurement process. As a result, common practice for physiological data collection in extreme environment is mostly limited to sensing technologies [26, 27].

Sensing technologies congregate several sensing modalities to measure and collect environmental and biomedical data. These modalities can be divided into bio-electric potential, electro-chemical, bio-mechanical, optical and acoustic sensing technologies.

Within the Athena research, Data scope of extreme environment exposure, austere environments impose strong limitations to technological monitoring technologies. Hence, only few technological approaches present the operational capability to be applied to such conditions.

These devices are supplied by a range of manufacturers internationally. The initial paradigm for the delivery of information from the devices was via a display monitor on the device. While some devices provided the ability to output data, this is not often a primary function as systems to ingest and process such high frequency data were not initially available. Many standards exist for data output from these devices and as a result a wide range of output formats exist with varying degrees of transparency and documentation available that detail the device output. There are multiple key elements that need to be considered for successful technology design for extreme environments. The operational design of the technology has to withstand the environmental conditions. The technology should be unobtrusive and should not interfere with the subject. This is detailed further in the Wearable Technology in Extreme Environments chapter within this book.

Ideally, the technology will be customized to the needs dictated by the environment, meaning the technological design to specifically monitor the physiologic parameter most likely to be involved in the regulatory compensation.

Processing sensor data is a Big Data problem. With an electrocardiogram signal at 250 readings a second, this translates to 21.6 million readings a day per person. An average heart of 60–80 beats a minute is approximately 100,000 beats a day. Heart rate, breathing rate and blood oxygen values derived every second result in 86,400 readings each a day. Environmental sensors can provide readings every second, minute, hourly or somewhere between. To make sense of this data, the proposed extreme environment approach for health, wellness, resilience and adaptation monitoring builds on big data based approaches for clinical decision support to ingest, integrate and make sense of this volume of data.

Behaviours in acquired signals from humans or the environment that are considered an anomaly under normal conditions may prove to be the norm in extreme environmental conditions. It is important therefore to calibrate any initial processing of the data within the devices that are used in non-extreme environments when reapplied for use in extreme environments.

Activity data in real-world operations, together with real-world or augmented reality training can be provided in real-time using online forms. These are completed by observers and require that observers have visual and auditory information as the operation unfolds. Within virtual reality training, game output can provide an automated approach to activity tracking.

Online tools can be created so that checklists and other quantitative and qualitative data can be entered online to enable the collection of further insights for health, wellness, adaptation and resilience in a way that enables direct integration with the other forms of data.

Further details on these challenges for each extreme environment will be presented later in this book as part of providing further details for various extreme environments.

3.3.3 Data Acquisition

To enable the health, wellness, resilience and adaptation analytics and information exploration monitoring components to utilize the data collected in the extreme environment, a means for the system or platform to acquire the data must be created.

The Data Collection sensing devices send their high frequency data streams to an output port that can be serial, Ethernet, Bluetooth or USB. Some devices, such as the Astroskin for astronauts or the terrestrial companion, the Hexoskin, require retrospective acquisition of the data from a data logger contained within the device for serial or USB connection. This data can then be acquired from the device and forwarded for buffering and transmission to the analytics, storage and information exploration components.

3.3.4 Data Buffering and Data Transmission

The component that manages forwarding the data acquired to the transformation, analytics, storage and information exploration components enables the Data Buffering and Data Transmission components and is known as edge computing (EC) [28].

EC facilitates efficient data processing in real-time with minimal or no latency. The Data Buffering component provides data message brokering. It manages packets of data messages for transmission through Data Transmission [29]. These packets can contain data tuples within a continuously or discontinuously flowing data stream from the human, environment or other sensor as well as activity, checklist and questionnaire data from webforms or other relevant extreme environment data.

The Data Transmission component provides the network connectivity component to enable the transmission of data to the cloud-based provisioning of the remaining HAaaS components.

3.3.5 Data Transformation and the Adaptive API

The Data Transformation component receives data from the Data Transmission component via cloud connectivity and transforms it into formats published by the Adaptive API for Data Producers. The adaptive API provides a standardized connection between the data producers that the Data Acquisition acquires data from and the data consumers in the Data Analytics, Data Visualization and Data Storage components [19] as shown in Fig. 3.3. The incoming data can be ingested from multiple sources simultaneously. These multiple sources can be different types of sources as well as multiple instances of the same sensors such as electrocardiogram monitoring data from multiple humans in the extreme environment concurrently.

Data forwarded from data produces are parsed, filtered and enriched with other data to translate the data into information and create linkages to enable the consumption of the data by various consumers as shown in Fig. 3.4.

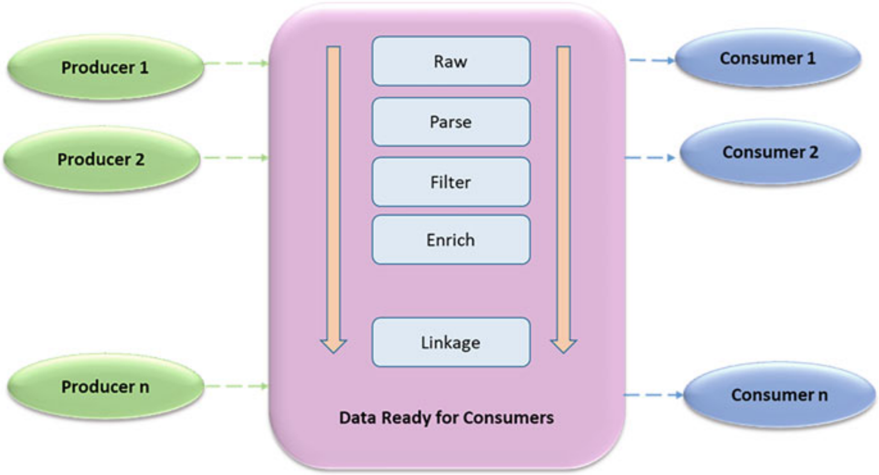

Fig. 3.4 Real-time streaming adaptive API [19]

3.3.6 Data Analytics

Data Analytics is the component that enables data to be translated into information, knowledge and wisdom. Data analytics can be performed in real-time or retrospectively. Real-time analysis can be performed to support the current operation utilizing the principles of stream computing as the data streams are provided for consumption by the Adaptive API from the Data Transformation component. It can be performed in real-time and retrospectively using the data stored within the Data Storage layer to support the current operation or to support knowledge discovery [29]. Within the extreme environment context, limitations in Data Transmission opportunities from the environment due to a lack of network infrastructure in a remote context, or safety concern for a tactical officer, may necessitate a design of post replay of data for stream computing based post processing of the data or in database generation of analytics.

The translation of data to information occurs when the data is given context and meaning. For example, when a stream of numbers is noted to be a stream of second by second heart rate values, or that a stream contains the millisecond value for each R peak in an electrocardiogram. Information is translated to knowledge when the information translates to a meaning. For example, when HRV reductions during a space flight indicate a negative/maladaptive response to the space environment.

To translate data to information and knowledge from data streams, temporal abstractions must be performed on the raw streams of data from the devices and those abstractions may need to be merged and analyzed together along with other abstractions and/or other information for more complex temporal abstractions. For example, baseline shifts in heart rate along with reduced heart rate variability during stressful situations.

Research directions in knowledge discovery initially focused on research relating to the creation of temporal abstractions and ontologies to support their definition [40]. Traditional data mining techniques are not able to provide time associated analysis when applied to streaming data. As a result, when these techniques are used to analyze raw physiological data streams, the slower frequency temporal abstractions from those streams, or other medical streaming data each element in the data stream is treated as its own discrete autonomous entity with no ability to associate it with the values before or after it in the stream. As a result, research in the area of temporal data mining has emerged [9].

McGregor outlined how transdisciplinary innovation led to a precision public health approach for health, wellness, resilience and adaptation [30]. In the extreme environment context, health, wellness, resilience and adaptation are broad thematic areas requiring analytical models.

Health analytics is enabled through clinical decision support to detect pathophysiological behaviours in physiological data streams or other health data that are onset detectors for a range of medical conditions. For example, analytics that watch for irregularities in an electrocardiogram that correspond with certain heart conditions. Even in the extreme environment context, life threatening health conditions should be a minimal set of clinical decision support analytics that are performed to assess the health of the person while in the extreme environment context.

Wellness analytics use sensor data and other data sources such as checklists and questionnaires to assess mental wellness states. Resilience analytics refer to analytics that assess the response to environmental and situation based stressors. Within this book resilience analytics are discussed for paramilitary and military tactical officers and similarities and differences to firefighters are also discussed. Adaptation analytics refer to analytics that monitor the adaption response. Within this book adaptation responses are outlined for space and diving.

By way of example, for the assessment of adaptation response, Baevsky [31] proposed the Functional State algorithm as a means to assess two dimensions of the adaptation response, namely system tension and functional reserves. The former relating to the immediate level of stress the body is under and the latter a sign of the degree of reserves to cope with that stress level. This is outlined further in this book.

As outlined earlier in the data collection section, it is important to note that behaviours in acquired signals from humans or the environment that are considered an anomaly under normal conditions may prove to be the norm in extreme environmental conditions.

3.3.7 Data Storage

To enable later use of the data for training, health and wellness or research purposes the acquired data together with any derived data should be stored by the Data Storage component. Data streams acquired from sensors together with the other forms of data such as checklist data, questionnaire results and other forms of qualitative data along with countermeasure data all require storage. In addition, video and audio files will also require storage.

For the sensor data, as a form of Big Data, relational database management systems together with Hadoop/MapReduce based approaches have been proposed for data storage of Big Data [32]; however, the latter lack the operational reliability that can be achieved in this context by relational databases for real-time use [9, 20].

For streaming data to be stored within the paradigm of a relational model the stream of data is segmented to a primitive element known as a tuple [41]. Tuples, at minimum, contain the data noting the entity the data stream was acquired from the stream value and the date and time for that value within the stream. Within the relational database, the tuples are then stored using the date and time, stream type and entity as a multipart key. The value is a non-key attribute [9].

The need for solutions for the efficient and effective storage of streaming data exists beyond this context of extreme environments to many other industry sectors and sensor data volumes are growing significantly due to the rise of Internet of Things (IoT). Neither the traditional relational database approach, the multidimensional database approach or the big data platforms such as Hadoop/MapReduce is built on the premise that data will arrive in a stream. In addition, these stream arrivals can occur continuously for months, years and even decades at a time. While stream computing approaches such as IBM InfoSphere Streams exist to process multiple interrelated real-time data streams as the data is acquired and before it is stored, more tailored techniques for storage and retrieval of that streaming data to support real-time and retrospective analytics are still needed [9].

Other data collected via Web forms, questionnaires and other forms of qualitative data require approaches for their storage that can utilize SQL and no SQL approaches. Video and audio files can be stored using standardized storage types such as MP4 and MP3, respectively. However, the annotations of events within the video and audio streams become activity based data streams that can be stored using the same approach as the streaming data from sensors as noted above.

3.3.8 Information Exploration

The information exploration layer enables passive visualization and active visual analytics. Visual Analytics enables dynamic "analytics reasoning facilitated by interactive visual interfaces" [33]. While static visualizations have a role for regular static information, providing visual analytics rather than static visualizations is seen as critical to "indispensable to include humans in the data analysis process to combine flexibility, creativity and background knowledge with the enormous storage capacity and the computational power of today's computers" [34]. Over time, the ways to display data, information and knowledge have evolved and human interaction has evolved from merely providing ways to display it to providing ways to individually interact with it. The information exploration layer provides visual approaches to explore knowledge, information, derived and raw data. This can be provided in real-time to support the current mission or retrospectively for individual or population based health, wellness, resilience and adaptation analysis and research.

In a review of novel visual representations of physiological data Kamaleswaran and McGregor [46] found that visual representations are challenged by user-preference and interaction challenges. They further noted the predominance of univariant displays rather than visualization and visual analytics approaches that were associated directly with health conditions [9].

The primary purpose of real-time displays of analytics in extreme environments are for the purpose of providing information about the person or people in the extreme environment from an immediate safety and life preserving standpoint. Information provided to the actual individual participant about their own current state has been limited to a need-to-know basis, as the subject is usually occupied with the effects of, and operation in, the extreme environment. How data is visualized has an impact on the subject. Red blinking alerts in a stressful situation may create a stress response, rather than having a calming impact. Distractions from additional, even unnecessary, information can prove to be fatal for the subject. A common practice is that information obtained from real-time analytics is monitored by an observer, who remains outside of the extreme environment. In this way, the observer can fully concentrate on the status of the person (people) and the person (people) can focus on their mission or task. Retrospective analysis on an individual or population helps to answer questions about the response to that particular type of extreme environment. As is evidenced in each of the chapters in this book that outline background context of the extreme environment, there has been research spanning years or even decades in each extreme environment setting to understand the impact of the environment on those who operate within it.

3.4 Continuous Health Monitoring and Digital Twins

A Digital Twin is an engineering construct that refers to a particular artefact and a computer model that closely reflects the state of that artefact virtually. Unlike more general or population approaches that are quite generic, the actual instance of an artefact—for example the engine of a specific aeroplane, or an individual person—and its/their model are closely coupled via a multitude of sensors [35]. As a result, the Digital Twin closely reflects the actual state of the artefact or individual. The acquisition of the data from the sensors enables digital representation and longitudinal persistence and its translation to information when there is understanding of what that data represents. However, to derive meaning and generate knowledge or wisdom relating to the current state or learn from past events, models need to be created. Digital Twins for humans have existed since the very first digital representation of electronic health records. However, the increasing prevalence of sensors and the rise of the internet of things in general provide great potential for Digital Twins to move from being very course to more fine grained representations. Models for a Digital Twin for humans are inherently more complex than for equipment due to the complexity of the human body. Monitoring people in extreme environments through the creations of platforms that are based on the information systems framework outlined in the prior section enables the creation of individualized digital twins. This is detailed further in the next section.

3.5 Computing Platforms for Continuous Health Monitoring

Utilizing the generalized framework proposed in the prior section, this section introduces examples of computing system components and computing platforms for continuous health monitoring for use in extreme environments. In prior work McGregor has led the creation of two computing platforms for continuous health monitoring, Artemis and Athena. Their positioning within the context of the generalized framework presented in the last section is shown in Fig. 3.5, and various chapters within the book provide more details in relation to Artemis and Athena deployments in extreme environments.

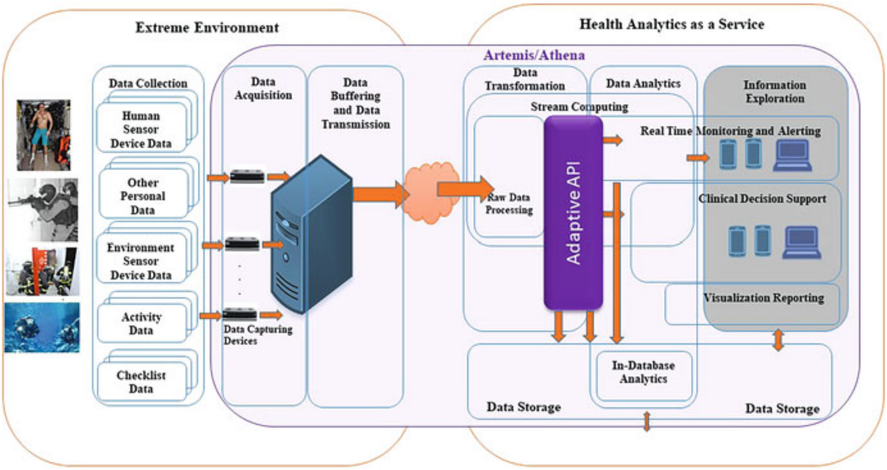

Fig. 3.5 The Artemis and Athena platforms within the context of the framework for extreme environment health and wellness monitoring

The remaining sections within this chapter summarize current directions within each of the components outlined in the generalized framework to demonstrate the current state of computing platforms for continuous health monitoring in extreme environments.

3.5.1 Data Collection

Many sensing devices have been used to enable data collection within extreme environments as detailed within the chapters of this book; however, a predominant challenge has been their lack of functionality to enable live streaming of data from the device to support real-time analytics and information exploration. Some devices such as the Zephyr bioharness by Medtronic that are marketed for regular use have been utilized by McGregor et al. within their firefighter, tactical officer and military extreme environment acclimation research [22, 23] and Andersen [38, 39] in extreme environments as they can be worn under PPE to provide some buffering to the extreme environment impacts. However, movement artefacts can still be a challenge.

The terrestrial Hexoskin biometric garment has been used by McGregor et al. [36, 37] to collect data from firefighter students while they train. It was further developed to propose the Astroskin/Bio M/Bio Monitor biomedical monitoring device that is now located on the International Space Station to monitor astronauts. The Cosmocard bioharness is used to monitor Russian Cosmonauts. Further details on both these monitoring approaches on the ISS are in the Space as an Extreme Environment—Technical Considerations chapter in this book. Sensing devices worn by humans in extreme environments need to be comfortable and not have negative implications such as skin irritations that could lead to infections. Wearing comfort, feasibility and accurancy of Actiheart, Hidalgo EQo2(Equivital), TICKR X, Fenix3, GENEActive, Axiamote PADIS 2.0, VSM1/Everion and Blue Thunder were assessed by Swiss Army Infantry Military Training school volunteers. They performed 10 different activities in a laboratory setting. Their heart rate and energy expenditure were assessed along with an assessment of wearing comfort. They reported that chest worn sensors had a greater negative impact than sensors worn on other parts of the body and were less likely to be work for extended periods when compared to sensors at other locations on the body [42].

The method of sensing such as those used traditionally for the sensing of the electrocardiogram do not work underwater presenting challenges for monitoring divers. This has hampered research efforts to monitor the diving adaption process as outlined further within the diving chapters of this book. Several environment sensors have been designed to collect and emit data as an internet of things (IoT) based approach. They are also used within climatic chambers for research and development [43].

While many checklists and forms exist, they are still predominantly paper based and require translation to online forms for electronic data collection. Within research projects, activity based information has been predominantly recorded manually on paper and sometimes electronic forms. McGregor has demonstrated the collection and acquisition of activity data using online forms within Athena [22, 23].

3.5.2 Data Acquisition

Many sensing devices have been used to enable data collection within extreme environments; however, a predominant challenge has been their lack of functionality to enable live streaming of data from the device to support real-time analytics and information exploration.

To enable the health, wellness, performance and adaptation monitoring to utilize the data collected in the extreme environment, a means for the system or platform to acquire the data must be created.

The Data Collection sensing devices send their high frequency data streams to an output port that can be serial, Ethernet, Bluetooth or USB. Some devices, such as the Cosmocard Astroskin for astronauts or the terrestrial companion, the Hexoskin, require retrospective acquisition of the data from a data logger contained within the device for serial or USB connection. The Zephyr bioharness enables live streaming from participants. As noted within the Data Collection section, acquisition of data from divers remains a challenge during their dive. As noted in [25] acquisition and integration of counter measure data is in its infancy.

3.5.3 Data Buffering and Data Transmission

Extreme environments can by nature hamper data transmission in many ways. Climatic extreme environments are often in rural and remote areas, where data transmission technology is not available. Electromagnetic waves (hence electromagnetic transmission, such as Wifi or Bluetooth) experience high absorption and attenuation underwater, which makes electromagnetic transmission underwater almost impossible. As noted in the following chapters, transmission strength triangulation can be used for life saving purposes to locate firefighters, but can put the lives of tactical offers in danger when their positions are made known. Within the Athena research, Data Buffering and Data Transmission of physiological, activity and environment data has been demonstrated from the Hexoskin and Zephyr biomedical monitoring devices, activity tracking webforms and environmental sensors within the Ontario Tech University's ACE Facility climatic chambers. The remaining Athena components demonstrating HAaaS are located at the Compute Ontario node within the Centre for Advanced Computing, Queen's University. Data was transmitted through a secure VPN within the Ontario Research and Innovation Optical Network (ORION). This is further detailed in the following chapters in this book.

3.5.4 Data Transformation and the Adaptive API

McGregor has demonstrated the use of the Data Transformation and the Adaptive API within the Artemis and Athena platforms. Within Artemis, they have been demonstrated within the context of real-time neonatal monitoring [19] and astronaut health monitoring. These components have been demonstrated within their use within Athena to ingest activity and physiological data to assess resilience for tactical officers while they train using a virtual reality game, ArmA 3 [44]. They have been demonstrated to collect physiological, activity and climatic data within acclimation training in the Ontario Tech University's ACE Facility climatic chambers for firefighter student real-world simulation training [36, 37]. The Athena Data Transformation and Adaptive API use with physiological, activity and climatic data has been demonstrated further with firefighter, tactical officer and military real-world deployment scene simulation for acclimation and resilience assessment and development [22, 23].

3.5.5 Data Analytics

While various tools are being used by different researchers to assess the participants in extreme climates the predominant information being derived and analyzed are the assessment of heart rate within the context of the Grossman [45] scale and heart rate variability. Various approaches such as Baevsky's functional state algorithm [8, 31] or other statistical methods such as SDnn are used to perform data analytics retrospectively. Within the Artemis and Athena platforms Data Analytics is performed in real-time through the deployment of stream graphs in Infosphere streams to calculate analytics based on the Grossman scale and SDnn during various activity windows. A real-time update of Baevsky's functional state algorithm has been proposed also. Retrospective derivation of other data analytics translations to information and knowledge occur within the Data Storage component contained in DB2 also.

3.5.6 Data Storage

Current research contains limited information pertaining to the ways that data collected in and acquired from extreme environments is stored. The reliability of relational databases in a companion Artemis operational deployment for real-time clinical decision support with Artemis Cloud demonstrates the reliability and availability performance of the IBM DB2 relational database demonstrating its reliability potential for use within the context of extreme environments also [20]. McGregor demonstrated the efficacy of the relational DB2 database to store physiological, activity and climate data together with derived analytics for her Athena deployments for tactical officers while they train using a virtual reality game, ArmA 3 [44] and the ACE Facility climatic chambers simulation training for firefighter, tactical officer and military real-world deployment scene simulation for acclimation and resilience assessment and development [22, 23].

3.5.7 Information Exploration

As noted earlier in the chapter, initial visualizations were printouts and displays on cathode ray tubes that were univariant, i.e., single parameter, displays of raw data. Visualization was evident even in the earliest experiments to create monitoring devices. It was evident during the earliest experiments in extreme environments for the preservation of life and scientific exploration of the impact of the extreme environment on the body. Even today, there is still a predominant focus for the display of univariant information [46] for health sensor data. There are great opportunities for newer approaches.

As is evidenced within the chapters of this book, solutions for information exploration within extreme environments through visualization and visual analytics are still in their infancy due in part to the predominance of retrospective analysis of data rather than real-time assessment.

Off-the-shelf tools for visualization and visual analytics of temporal abstractions and complex temporal abstractions from medical device data streams are in their infancy [9]. In this book some examples of the use of Microsoft Power BI are provided, but these provide access to data from the database rather than receiving continuous real-time streams of analytics to display. In prior work Kamaleswaran and McGregor have demonstrated a purpose built visualization heat map technique to display different types apnoea events over time [47], and these approaches have relevance for assessing the interplay of breathing, heart rate and blood oxygen over time in extreme environments.

3.6 Conclusion

In this chapter, we have presented an overview of sensing devices, computing systems and platforms along with the information systems frameworks within the context of extreme environments from a generic perspective. The remaining chapters within this book explore these concepts further.

While military groups have the economies of scale and security requirement for in house hosted platforms, cost effective solutions that advance the techniques for preservation of life improve resilience and adaptation development at an individual level may be less achievable in house for smaller organization groups such as the paramilitary organizations, tactical teams within a police department and local fire departments. As a result, these may be better provisioned utilizing “As a Service” cloud-based provisioning of solutions for smaller extreme environment groups.

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Part II
Water

Chapter 4
The Underwater World and Diving Physiology

Michael Bennett AM and Tobias Cibis

4.1 History of Diving and Underwater Medicine

The underwater world can be considered as one of the first extreme environments human kind explored. Diving has been utilized in multiple ways for domestic, commercial and military purposes. Recreational diving, especially using scuba (Self-Contained-Underwater-Breathing-Apparatus) became popular in the second half of the twentieth Century. Nowadays, ancient breath-hold diving practices, primarily developed for gathering food and valuable commodities, are slowly giving way to compressed gas diving, and recreational diving has developed into a variety of different modalities. The comprehensive history of diving is far too complex (and fascinating) to effectively summarize in the few pages available; however, the following are a few key events in the development of diving equipment and the field of diving medicine.

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4.1.1 Diving in Ancient Times

The earliest form of diving was breath-hold diving. Archaeological evidence suggests breath-hold dives were used to harvest sponges, food, pearls and corals. These domestic purposes were soon followed by military and salvage efforts [1]. In 900 BC breath-hold divers were used in the Trojan wars to sabotage and attack enemy ships, and Alexander the Great used divers for underwater demolition during the Siege of Tyre around 332 BC [1, 2]. It was said that Alexander the Great descended in a diving bell himself; however, details are sparse and some of the stories sound fanciful.

Many tracts and diagrams describing diving equipment and techniques have survived from ancient and mediaeval times. Many are attributed to famous historical figures such as the Greek philosopher Aristotle in the fourth century BC and the Italian polymath, Leonardo da Vinci. Although it is not known if these sketches were ever realized and developed, they attest the desire to explore the underwater world and remain submersed for an extended time.

4.1.2 Surface Supply Diving

In 1690, Edmond Halley designed his first diving bell with air supplied at atmospheric pressure. He subsequently improved his design in 1719, by cleverly providing air to the bell from two barrels suspended below the bell (and therefore at higher pressure than the bell). Divers used this bell to depths of 18 msw and apparently stayed submerged for up to 1.5 hours [3, 4].

In the 1700s the development of compressors allowed a shift from underwater to surface compressed air supply. This also enabled the development of helmet-hose diving apparatus. Surface-supplied compressed air diving became the prevailing commercial diving technique, and this remains the case up to the present day in many industries [5, 6].

The effectiveness of these new techniques was demonstrated in the salvage operation of the H.M.S. Royal George in 1832. A diving helmet was perfected by Augustus Siebe. The Siebe helmet and closed dress were the common diving equipment for commercial divers [1]. Siebe's diving proved to be so successful, that it established the predominant compressed air surface supply technique in use to this day. The present US Navy Mark V Deep-Sea Diving outfit is only a modernized iteration of Siebe's initial design.

4.1.3 Modern Diving

In 1800 with the then state-of-the-art diving equipment, divers were able to reach depths of 50 m for an extended period. With the venture into depths beyond 30 m divers started to experience the mysterious joint and neurological effects that have become known as decompression sickness (DCS), which caused significant injury and death to many divers.

While diving gear kept developing, the effects of compressed air breathing in environments with elevated ambient pressure also received attention in different setting. During the Brooklyn Bridge project, from 1870–1873, there were 110 cases of DCS reported among the 600 workers employed. Andrew Smith, the physician in charge was the first to use to term "caisson sickness."

In 1878, Paul Bert published his work "La Pression Barometrique" [7], which is considered the founding document of aeronautical medicine. He described theories for both, hyperbaric and hypobaric exposures and their practical applications. His descriptions included that mountain sickness was due to hypoxia and to survive at extreme altitude, oxygen must be breathed, and that higher pressures would require the breathing of lower pressures of oxygen to sustain life. He also described the toxic effects of hyperbaric oxygen in animals, which is now known as acute oxygen toxicity. Bert discovered that rapid decompression can cause nitrogen bubbles to form in tissue and blood. These fundamental findings were the first steps in research towards the understanding of DCS.

It was not until the twentieth century that J.S. Haldane and colleagues [47] derived satisfactory mathematical concepts to describe and design of countermeasures for the physiological problems associated with DCS (1907). The mathematical model reflected the behaviour of inert gas inside the human body and was the initial step towards the development of safe decompression tables. The first tables were designed employing the assumption that DCS could be avoided by not exceeding a 2:1 pressure gradient between tissues and breathing gas during ascent. Although later studies revealed the details of Haldane's model were not entirely correct, his tables had a significant impact preventing many divers from developing DCS—a condition colloquially called 'the bends'.

In the twenty-first century, diving medicine and technology research have together contributed to better addressing the physiological issues and minimize the risk of diving injury. Advances in diving equipment, the development of both large-scale manufacturing and standardized training organizations, have allowed the popularization of diving such that this environment is now accessible to the average man. The design of a proper demand-regulated air supply from compressed air cylinders by Cousteau and Gagnan in 1943 was the founding step towards the scuba equipment as we know today.

4.1.4 Diving Modalities

The following are some of the commonly practiced advanced diving modalities.

Rebreather Diving

The purpose of a rebreather diving set is to recycle a diver's exhaled gas so it can be re-used safely during a dive. Rebreathers may be semi- or fully-closed systems and are increasingly used for recreational, scientific, and technical diving because of both the ability to allow extended time underwater and increased depth capability [8–10].

The traditional scuba set is a fully open-circuit system where no rebreathing occurs. Exhaled gas is simply vented to the surround water. In contrast, while details vary, a rebreather collects exhaled gas in an expandable container (counterlung), passes it through a device to absorb carbon dioxide (scrubber), and replenishes oxygen to the desired concentration before being available for the subsequent inhalation. Thus, the breathing loop is more complex than a simple second stage diving regulator [8, 9].

Mixed-Gas Diving

Often combined with the use of a rebreather, divers employ breathing gases other than air in order to venture to greater depths. Deep diving brings with it a number of physiologic challenges that require close attention to the partial pressures of inhaled gases. Nitrogen (80% of normal air) becomes increasingly narcotic above a partial pressure of about 3.5 atmospheres, and oxygen increasingly toxic at partial pressures above about 1.6 atmospheres. These problems can be addressed by the addition of a diluent in the form of a non-narcotic inert gas (most commonly helium) but involved careful attention to ensure appropriate gases are used throughout a dive—including descent and ascent. Planning the use of 'mixed-gas' diving is complex and potentially hazardous.

The most common mixture is 'Trimax', a combination of oxygen, helium and nitrogen. Mixed-gas diving techniques were developed from commercial and military operations but are increasingly popular in 'technical' recreational diving.

Saturation Diving

When scientific or commercial purposes dictate that long periods (days to weeks) be spent at depth, saturation diving is the obvious solution. It is often complicated, expensive and time consuming to repeatedly dive and resurface while conducting a long-term task—for example, a scientific survey or a construction project. Saturation diving avoids these inefficient repetitive dives and exploits the fact that after a diver is fully saturated with the breathing gas in use at depth, then no further decompression time is required—regardless of the length of time under pressure.

Saturation operations involve the use of a habitat where the divers live between working tasks. Such habitats may be actually compressed vessels placed on board a ship, or submerged at or close to the working depth. Saturation may be undertaken at quite modest depths and yet save many hours of decompression time over the course of a project. Such diver require long terminal saturations for each diver and take many days if the saturation is at significant depth.

Today, saturation divers are conducted between 30 m and 300 m. A dive to 300 m would take approximately eleven days or more of decompression. Such extensive decompression time required to ascent to the surface is very expensive and a great logistical challenge.

4.2 Diving Physics—The Underwater Environment

4.2.1 Introduction

All matter is composed of atoms or bonded groups of atoms called molecules. These atoms or molecules are in constant motion oscillating around a mean position but continually rebounding off each other in all directions. Each atom and molecule interacts at a close range with all others through weak forces (either attractive or repulsive) known as Van der Waal forces [11]. Van der Waal forces are responsible for much of the observed behaviour of matter including the liquefaction of gases below a certain temperature and the ability of flies to crawl across the ceiling. They are due to fluctuating polarizations as a consequence of quantum dynamics and are distinct from the more powerful forces of covalent or ionic bonding.

Covalent bonding (also called molecular bonding) is a chemical bond that results from the sharing of a pair of electrons between atoms and often results in a more stable configuration—for example the formation of hydrogen (H_2) from two single hydrogen atoms. Ionic bonding similarly involves the sharing of electrons but involves electrostatic attraction between oppositely charged ions—for example common salt is formed from sodium ions (Na^+) and chloride ions (Cl^-) to form NaCl, which has no net electrostatic charge.

The complex interaction between these forces, heat (often expressed as the temperature T) and pressure P are responsible for the manifestation of the three states of matter: solid, liquid and gas. A solid consists of molecules packed together in a lattice construction. If heat is added, the molecules begin to move with greater amplitude and take up more space, thereby weakening the forces between them. At a high enough temperature the forces are no longer strong enough to hold the molecules in the lattice and the solid breaks down to a less structured state usually called liquid. If the temperature is further increased, each molecule gains more kinetic energy and, above a certain temperature, enters the gaseous state. Higher pressures will increase the temperature required for the transformation from solid to liquid and liquid to gas for any substance. Many of the interactions between these elements are described by a series of ‘Laws’, a number of which are highly pertinent to divers.

Table 4.1 Common conversion of pressure units

	ATM	ATA	Bar	mmHg	mmH$_2$O
ATM	1	1.033	1.013	760	10332.56
ATA	0.968	1	0.981	735.56	10000.3
Bar	0.987	1.02	1	750	10197.44
mmHg	$1.316 \cdot 10^{-3}$	$1.36 \cdot 10^{-3}$	$1.33 \cdot 10^{-3}$	1	13.6
mmH$_2$**O**	$9.67 \cdot 10^{-5}$	$9.89 \cdot 10^{-5}$	$9.81 \cdot 10^{-5}$	0.0736	1

Pressure

Pressure P is the most important environmental quantity that a diver is exposed to and is defined as a force F acting on a unit area A:

$$P = \frac{F}{A}. \tag{4.1}$$

Pressure is a highly relevant concept in underwater exposure and diving medicine and can be presented in a potentially confusing myriad of units. Throughout this chapter pressures are presented as atmospheres absolute (ATA) or kilopascals (kPa) depending on the context. For conversion to all commonly used pressure units see Table 4.1.

A depth of approximately 10 msw (metre of sea water) or 33 fsw (feet of sea water) equal to one atmosphere, or one bar or 101.3 kPa (kilo Pascal) of pressure. The ambient pressure acting on a submerged person is the addition of two components: the pressure of a water column and the atmospheric pressure under which the water column lies. Water pressure is the product of water depth and density, while the atmospheric pressure is the pressure exerted by the earth's gaseous atmosphere at the water surface level. Often we accept the air pressure as the average at global sea level, for which we use the term '1 atmosphere absolute' (1 ATA or 101.3 kPa). The density of water is one kilogram per cubic metre ($1 \frac{kg}{m^3}$), so that at the depth of 10m, the pressure exerted by the water column is $10\,m \cdot 1 \frac{kg}{m^3}$ ($= 100\,kPa$). Thus, at 10 m depth, a diver is subject to an ambient pressure of 201.3 kPa—a pressure very closely equivalent to 2 ATA (202.6 kPa).

4.2.2 *The Gas Laws*

The relationships between pressure, volume and temperature of gases are particularly relevant to divers, so much so that many important practical diving issues rely on an understanding of the consequences of these relationships. They are summarized in a series of 'Gas Laws' outlined here.

Boyle's Law

The relationship between pressure and volume for a given mass of gas at constant temperature.

If the mass of a gas and its temperature are kept constant, the gas volume is inversely proportional to the acting pressure. Boyle's law can symbolically be formulated, denoting initial pressure and volume P and V and submersed pressure, P_{sub} and P_{sub}, respectively:

$$P_i\, V_i = P_{sub}\, V_{sub} = const. \tag{4.2}$$

Charles's Law

The relationship between the volume and temperature, for a given mass of gas at a constant pressure.

If the mass of gas is not changed and pressure is kept constant, then the gas volume will vary linearly with temperature

$$\frac{V_i}{T_i} = \frac{V_{sub}}{T_{sub}} = const. \tag{4.3}$$

Ideal Gas Law

'Ideal gas' is a theoretical gas composed of many randomly moving point particles that are not subject to interparticle interactions. For practical purposes the common gases used in diving can be assumed to be 'ideal'.

The ideal gas law reflects a combination of Boyle's and Charles's Laws and relates to the measurable quantities pressure, volume and temperature. Considering changes in ambient pressure, gases will contract or grow in their volume and can be described with the *Ideal Gas Law*. The law states that the product of absolute gas pressure, P and volume,V must equal the product of the mole fractions, n, the Avogadro's gas constant, R and the absolute temperature T,

$$P\, V = n\, R\, T \tag{4.4}$$

It is the most important law regarding gas systems underwater. For the sake of completeness, it should be noted that at very high pressures and low temperatures, gases no longer obey these gas laws—they can no longer be regarded as 'ideal'. No current efforts of human exposure are anywhere near this threshold.

Dalton's Law

The contribution to total pressure for each gas in a mixture of gases.

Diving gases are rarely composed of a single gas, but rather are a combination of different gases. Each gas exerts a partial pressure that contributes to the total pressure of the gas mixture. Each partial pressure is the pressure that the gas would exert if it occupied the space by itself. The total pressure exerted by a mixture of gases P_{abs} is equal to the sum of the partial pressure of each of the component gases. Put another way, if a mixed gas is composed of three different gases, the total pressure of the gas will equal the pressure of each of the individual gases added together. The atmosphere at sea level is an example, being composed of 21% oxygen, 78% nitrogen and 1% 'other gases' (principally the noble gases). Thus:

$$P_{abs} = 0.21 \cdot P_{O_2} + 0.78 \cdot P_{N_2} + 0.01 \cdot P_{noble} = 1\,ATA. \tag{4.5}$$

Henry's Law

The relationship between the partial pressure of a gas in contact with a liquid and the amount of that gas dissolved in the liquid.

Whenever a gas is in contact with a liquid, a portion of the gas molecules will dissolve in the liquid. Different gases will dissolve to a greater or lesser extent—each has a unique 'solubility' in every liquid. This factor of solubility is important for underwater exposure and diving because significant amounts of gases are dissolved in body fluids and tissues during exposure to increased pressure while diving. As the pressure increases so does the amount of gas dissolved in a liquid. The relationship between the amount of dissolved gas and pressure is called Henry's Law, which states that the volume of gas dissolved in a liquid is equal to the product of Henry's constant k and the partial pressure of the gas P_{gas}.

$$\frac{P_{gas}}{k_h} = c_{gas}. \tag{4.6}$$

It follows that if the gas partial pressure is doubled, then the amount of gas in solution at equilibrium will double, and conversely, if the gas partial pressure is halved then half of the gas will leave the solution. Some gases are more soluble than others and some liquids are better solvents than others. For example, while nitrogen is five times more soluble in fat than water, helium is not very soluble in fat (this may be relevant in regard to the narcotic effect of Nitrogen but not Helium—see below).

Fick's Law

The relationship of a flux of particles along a concentration gradient.

Gases dissolved in liquids move randomly throughout the liquid in a thermodynamic process and this results in an even distribution of dissolved gas throughout the liquid in a process described as diffusion. When dissolved gas is introduced into a liquid at any particular point, the pressure will be equilibrated throughout the liquid. Another way of describing this phenomenon is that diffusion is the random movement of particles from a region of higher concentration to a region of a lower concentration.

Fick's first law describes that a flux density j is linearly proportional to a concentration gradient $\frac{\partial C}{\partial x}$ with the diffusion constant D:

$$j_x = -D \cdot \frac{\partial C}{\partial x}. \tag{4.7}$$

The flux density j relates to a rate of change of a quantity (e.g. gas particles) with position, describing a transport of the quantity [12]. Hence, a concentration gradient causes a diffusion of particles.

In diving scenarios, increased ambient pressures translate to varying partial gas pressures, creating gradients across anatomical barriers within the body. While the diffusion rates of a gas within a continuous body of liquid is constant, the presence of a barrier within the liquid substantially affect the diffusion rate of the gas. Consequently, it is important to understand the physical laws that govern diffusion of dissolved gas across membranes as they heavily inform the gas exchange process of bubble growth. Fick's law describes the rate at which a dissolved gas diffuses across a barrier given certain properties of the barrier and the gas.

$$\frac{dV}{dt} = D \cdot A \cdot \frac{\Delta P}{d}. \tag{4.8}$$

The equation states that the rate of diffusion $\frac{dV}{dt}$, indicated by volume changes over a period of time, across permeable barrier is determined by the chemical nature of the membrane itself , the surface area of the barrier A, the partial pressure gradient ΔP of the gas across the barrier, and the thickness of the barrier d.

4.3 Diving Medicine

4.3.1 Diving Physiology

The human body is well-adapted to the terrestrial environment, performing best at close to one ATA while breathing air in a gaseous environment. The principal challenges during diving relate to both changing pressure and immersion. Apart from the obvious challenges in successfully supplying the body with oxygen and eliminating carbon dioxide whilst both immersed and dealing with a grossly increased ambient pressure, the much greater density of water compared to air means the body can be uniquely subject to a significant pressure gradient if upright in the water column. Unsurprisingly, significant physiological changes occur when the body is immersed and subjected to increased pressure.

4.3.2 Physiology of Immersion

4.3.2.1 The Diving Reflex

Diving mammals are highly adapted for immersion. One of the most prominent changes on immersion is the rapid onset of a number of physiological changes that extend the period during which oxygen can be supplied to vital organs—

together these are often called the *diving reflex*. These changes include a pronounced reduction in heart rate (bradycardia) and a selective regional constriction in arteries that produce a 'selective ischaemia' resulting in preferential perfusion of oxygen sensitive organs.

Humans retain a vestigial diving reflex, particularly on exposure to cold water on the face [13]. Initially there is a restriction of blood flow to the peripheries (peripheral arterial vasoconstriction) and a reflex bradycardia, probably via a trigeminal nerve–brainstem reflex arc. Efferent parasympathetic pathways mediate bradycardia and efferent sympathetic pathways mediate peripheral vasoconstriction. Similar responses have been noted during neurosurgical procedures close to the trigeminal nerve and have been called the *trigeminocardiac reflex* (TCR).

While there are similarities between the TCR and the diving reflex, the latter is characterized by a degree of hypertension, while in contrast, hypotension is a feature of TCR [16]. The difference may well reflect the prominent venoconstriction secondary to hydrostatic forces on immersion, reinforced by cooling peripheries and resulting in a shift of blood into the central veins and pulmonary circulation [14]. The net result of increased venous return, increased stroke volume and the reflex bradycardia is a modest increase in both cardiac output and arterial pressure.

The increased venous return also stretches the atria, stimulating atrial receptors to release atrial natriuretic factors (ANF) and an associated decrease of anti-diuretic hormone (ADH), resulting in unopposed diuresis [15].

4.3.2.2 Respiratory Effects

Immersion also impacts respiratory mechanical factors [15]. When the diver is upright (particularly with head out of the water), the chest is exposed to a significantly higher pressure than the mouth. At rest, the pressure in the alveoli will be equal to the ambient pressure underwater (1 ATA + water column pressure), while the mouth will be at 1 ATA—encouraging egress of gas from the lung. On inspiration, a great relative negative pressure will need to be generated at the mouth in order to achieve gas flow into the lungs. The work of breathing will increase and the central shift of blood into the thoracic cavity will be enhanced, reinforcing the haemodynamic changes already described by Camporesi [15], Fig. 4.1.

4.3.2.3 Thermal Considerations

Immersion predisposes the diver to hypothermia because of the high thermal conductivity of water compared to air. Hence, except for relatively short, shallow exposures in warm tropical waters, divers need to wear some form of thermal protection. Even mild degrees of hypothermia may threaten the diver through impairment of psychomotor ability.

When immersed, most heat is lost through conduction and convection. Heat is exchanged through the skin into the water immediately surrounding the body and

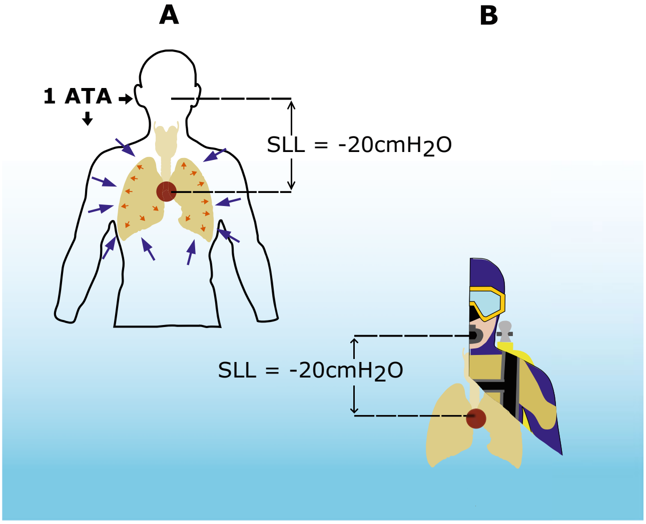

Fig. 4.1 Respiratory consequences of immersion for an individual breathing with head out of water (Panel A) and a scuba diver upright in the water (Panel B). **Panel A**: The distance between the water surface and the centroid of the lung is 20 cm, and a pressure equivalent to that depth is exerted on the thorax and all structures contained in it. This pressure exerted by the water column is $0.2\,m \cdot 1\,kg/m^3 = 1.96\,kPa$. Typically, a quiet inspiration requires a negative pressure of around 5 cm water (0.49 kPa). Immersion requires the individual to increase the negative pressure required to inspire by a factor of five. **Panel B**: A scuba diver upright in the water has a regulator that equilizes the breathing air pressure to that at the mouth. The consequences are the same as Panel A [17]

subsequently carried away through convection. The rate of heat transfer will depend on a number of factors including skin blood flow, the nature of any protection worn and the rapidity of movement of water over the body surface, but primarily depends on the physical characteristics of thermal conductivity and specific heat capacity. Thermal conductivity is a measure of the ability of a substance to transfer heat and is measured as the amount of heat transferred per unit time and surface area, divided by the temperature gradient. For example, at 20°C, the thermal conductivity of water is about $0.59\frac{W}{m \cdot K}$. Specific heat capacity is the amount of energy (joules in the form of heat) that must be added to a standard mass of a substance (1 kg) in order to cause an increase of one-degree Kelvin (1 K). For water at a temperature of 25°C, the energy needed to increase one kilogram of water by 1 K is 4,179.6 joules, meaning that the specific heat of water is $4179.6\ \frac{J}{kg \cdot K}$. Heat is lost much more readily in water than in air because water has a thermal conductivity approximately 23 times that of air and a specific heat about 3500 times that of air.

These differences between air and water mean the thermoneutral range (where an unclothed human can maintain core temperature without an increase in metabolic rate) in water is very narrow (around 34° to 35°) compared to that of air (from about 21° to 30°) [18].

4.3.3 Physiology of Exposure to High Pressure

4.3.3.1 Respiratory Effects

Gases are composed of molecules in constant random motion and separated from each other by relatively large distances. As the pressure is increased the molecules are pushed closer together and the mass of matter per unit volume is increased. We express this increase in matter per volume as density. The density of any breathing gases will be increased in a direct proportional relationship with ambient pressure, such that doubling the ambient pressure will double the density of any single gas if the temperature is held constant Fig. 4.2.

Increased density requires an increase in the work of breathing in order to move the same volume of gas. The practical implications are that the maximum breathing capacity (MBC) is reduced at higher pressures and ultimately the oxygen consumption required to 'shift gas' exceeds the oxygen supplied to the alveoli from that effort. Under those conditions, the increased work of breathing is the limiting factor for survivable depth exposure. The drop in MBC is about 50% at the relatively modest depth of 30 metres of seawater (msw)—4 ATA ambient pressure [15]. These density related problems can be partially ameliorated by good design of breathing apparatus and the use of gases with low density to replace the nitrogen in air (density at 1 ATA = $1.2\,\frac{kg}{m^3}$). Gases in common use to assist with deeper diving include helium (density at 15°C and 1 ATA = $0.08\,\frac{kg}{m^3}$).

Breathing gases at higher densities and where there is a column of water pressure to overcome both contribute to increasing the relative negative pressure within the chest compared to the mouth. This negative pressure may produce problems at the level of the alveolar capillaries through transudation of fluid from capillaries into the alveolar space.

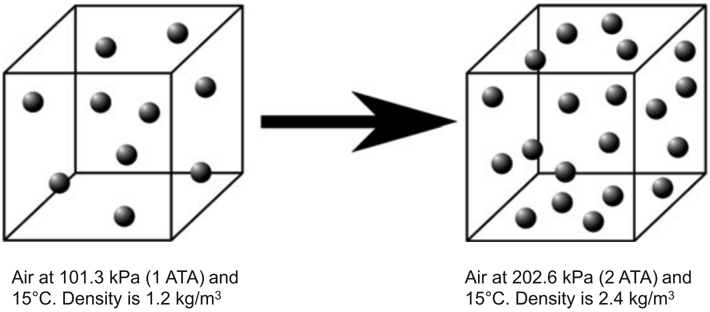

Fig. 4.2 Density and pressure. As ambient pressure increases, so does the density. Here a doubling of pressure from one to two atmospheres (surface to approximately 10 metres of seawater) also doubles the density—there are twice as many molecules in the same volume. Air is of course a mixture of gases but represented here as uniform molecules

The increased work of breathing may also have consequences related to the control of breathing. Under normal conditions, the main determinant of minute ventilation is tight control of arterial carbon dioxide tension ($PaCO_2$) through pH-sensitive chemoreceptors in the carotid bodies. Increased CO_2 production (due to any cause of increased metabolic rate) will rapidly result in an increase in ventilation, thus bringing the $PaCO_2$ back to normal. Neural pathways also have role specifically relating to exercise where ventilation increases almost immediately on commencement of exercise [19]. When the work of breathing increases, more CO_2 will be produced resulting in both increased ventilation and a further increase in $PaCO_2$. Eventually, a new level of ventilation will be found. If the ventilation required is excessive for the individual concerned, the result will be dyspnea (breathlessness) and the diver will be unable to continue the current level of activity for a sustained period. At the extreme, $PaCO_2$ may climb rapidly as the diver is unable to sustain the ventilation required, leading to increasing respiratory distress and eventual unconsciousness from hypercarbia. This sequence of events is a direct result of increased gas density and have been implicated in diving fatalities [20].

Some individuals seem more tolerant of rising $PaCO_2$, exhibiting a ‘blunted’ ventilatory response. It is not clear if this is a form of acclimatization in experienced divers, an innate variation or a combination of these factors. For whatever reason these ‘carbon dioxide retainers’ are over-represented in the diving population and may represent a danger to themselves and others if impaired by rising $PaCO_2$ and by increased susceptibility to oxygen toxic seizures or enhancement of nitrogen narcosis (see Sect. 4.3.4.1) [15]. Screening for these individuals in commercial and military diving operations has been advocated by Elliott and others [21].

Overall, immersion and breathing compressed gases tend to push divers towards hypercapnia. In addition to the mechanisms discussed above, there is some evidence that immersion causes the respiratory centre to exhibit a reduced responsiveness to hypercapnia and that this tendency may be exacerbated by inert gas narcosis (usually nitrogen) [22]. Many scuba divers have also learned the technique of reducing their minute ventilation deliberately in order to conserve a limited supply of breathing gas at the cost of tolerating a higher than normal PCO_2. The most common technique involves deliberately long pauses between inhalation and exhalation and is often referred to as ‘skip breathing’. Higher $PaCO_2$ may increase the risk of central nervous system oxygen toxicity through cerebral vasodilatation and many of these divers complain of headaches after diving from the same mechanism.

4.3.3.2 Barotrauma

All places in the body where gas exists will be subject to Boyle’s Law. This includes the middle ear and sinuses, lungs, gut and potentially any carious teeth. All these sites are potentially at risk of damage as a direct result of changes in pressure and therefore of volume in an enclosed space. The general term for any injury relating to the expansion or contraction of volume (or the increase or decrease in pressure) is *barotrauma*, although among divers these problems are often referred to as a ‘squeeze’—such as ‘ear squeeze’.

Middle Ear and Sinus Barotrauma

Most barotrauma is associated with the exposure to increasing ambient pressure (on descent). The most common example is the middle ear (middle ear barotrauma—MEBT). In a normal individual, the middle ear is an air-filled space between the tympanic membrane (eardrum) and the skull including two membranous parts called the round and oval ‘windows’. The space is spanned by the three ossicles—small bones articulated so as to amplify the vibration of the tympanic membrane and transmit those vibration to the oval window and thence to the inner ear. The middle ear is connected to the nasopharynx by the Eustachian tube, which serves to keep the middle ear pressure very close to the ambient pressure without conscious effort (Fig. 4.3).

In man, the Eustachian tube is partly surrounded by bone (Fig. 4.3) and partly by the soft tissues of the nasopharynx. Abrupt changes in pressure can easily block the part of the tube within the soft tissues and leave the middle ear at a negative pressure relative to the ambient. This is felt as pressure building in the ear and can become rapidly painful as the pressure differential rises. When the pressure differential is low, the Eustachian tube can be forced open by applying positive pressure within the nasopharynx and pharynx (often called the *Valsalva manoeuvre*) resulting in air being introduced to the middle ear to equalize the pressure with ambient. Some individuals find this easy to achieve with minimal effort, while in others this equalization is difficult or impossible. For everyone, however, past a certain differential pressure the Valsalva no longer works and barotrauma of the middle ear can only be avoided by reducing the ambient pressure (ascending). If a diver continues to descend, the increasing ambient pressure can ultimately result in tympanic membrane rupture and the ingress of water into the middle ear.

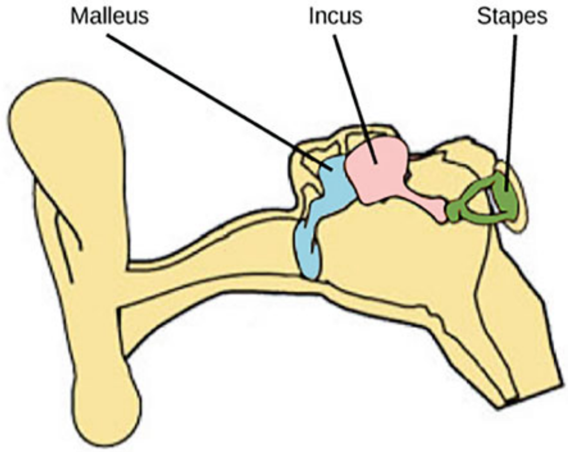

Fig. 4.3 Middle ear anatomy. The middle ear contains three small bones labelled here and is air-filled in health with a connection to the nasopharynx that allows equalization of pressures between ambient and the middle ear space

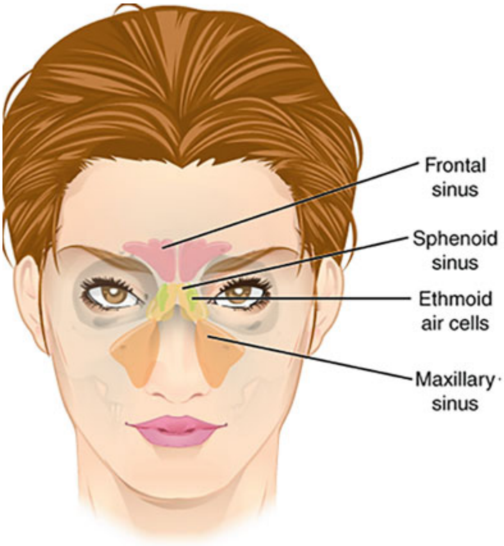

Fig. 4.4 A frontal view of the paranasal sinuses. All communicate with the nasal passage but can be easily blocked by mucus and inflammation of the mucosa lining the passages. In some individuals this may be a frequent occurrence or a chronic state

Lower grades of MEBT result in anything from reddening of the drum, transudation of fluid across the mucosa lining the middle ear to bleeding within the drum and middle ear space. A degree of MEBT is a common complaint of divers and a frequent cause of dive abandonment.

A similar problem occurs in the respiratory (or 'paranasal') sinuses located behind the forehead and cheekbones (Fig. 4.4)

Barotrauma of both the middle ear and paranasal sinuses is most commonly encountered with increasing pressure as a result of descent through the water column. Occasionally problems can arise during a reduction in pressure (barotrauma of ascent or 'reverse squeeze'). These can be highly problematic because of the need for the diver to eventually reach the surface.

Pulmonary Barotrauma

Barotrauma to the lungs (pulmonary barotrauma or PBT) is the one type of barotrauma that is more commonly a problem of ascent than descent. Unlike MEBT or sinus barotrauma, PBT is a potentially fatal problem due to either the entrainment of gas into the pulmonary circulation or to the presence of gas within the chest but outside the substance of the lung.

PBT has been well reviewed by Mitchell in 2016 [23]. As with other barotraumas, it is a direct result of Boyle's Law and occurs when an obstruction to the egress of gas from the lungs occurs during ascent, resulting in a combination of over-pressure and over-distention of the lungs. The pathophysiological relationship between pressure and volume changes is complex and variable between individuals. There is evidence that higher pressures within the lung can be tolerated if the chest is bound so that it cannot expand, suggesting the problem is primarily one of over-expansion

[24]. Gas under pressure disrupts the substance of the lung and is forced out of the alveoli and small airways into the tissues. The gas can track to several different locations, causing distinct pathological syndromes.

Firstly, the gas may track into disrupted capillaries and veins surrounding the alveoli and thence embolize into the pulmonary veins, left heart and be ejected from the left ventricle in the arterial circulation. The most important consequence is the distribution of these bubbles of gas through the cerebral circulation, resulting in cerebral arterial gas embolism (CAGE). CAGE is a true diving emergency and can be rapidly fatal or result in permanent brain injury.

Secondly, the gas may be released into the intrapleural space—the potential space between the lining of the lung and the chest wall. An accumulation of gas here is called a pneumothorax and may restrict ventilation if the volume is large and pressure starts to rise as more gas enters the space and the diver rises through the water column. If the pressure and volume of a gas collection threaten respiration, this is another true diving emergency and can be rapidly fatal unless the gas is released by puncturing the chest wall to facilitate a communication with the outside air.

Finally, the gas may track up the lining of the small airways and manifest in the mediastinum or subcutaneously in the tissues of the neck and face where it is called '*surgical emphysema*'. This manifestation can be impressive but is rarely life-threatening.

4.3.4 Physiology of Exposure to Individual Gases

4.3.4.1 Inert Gas Narcosis

Inert gas narcosis (IGN) refers to a clinical syndrome characterized by impairment of intellectual and neuromuscular performance and changes in mood and behaviour by a gas, which undergoes no metabolic alteration in the body (i.e. it is 'inert'). These changes become more profound with increasing partial pressure of the gas concerned and will ultimately lead to unconsciousness. In compressed air exposure, these changes are due to nitrogen. IGN has been comprehensively reviewed by Bennett and Rostain [25].

The effects of nitrogen breathing at pressure are well-recognized by divers and often called '*nitrogen narcosis*', '*the narks*' or '*raptures of the deep*' (l'ivresse des grandes profondeurs), the latter term coined by Jacques Cousteau. The narcosis, although highly variable, places a practical depth limit to scuba diving with compressed air at approximately 40–50 metres. Effective work at greater depth requires the substitution of a less narcotic respiratory diluent such as helium or hydrogen. It is highly probable that many "unexplained" scuba deaths have been induced by the insidious onset of nitrogen narcosis.

IGN is produced by an increased partial pressure of most inert gases, with helium a notable exception. The effect is highly analogous to that of anaesthetic gases

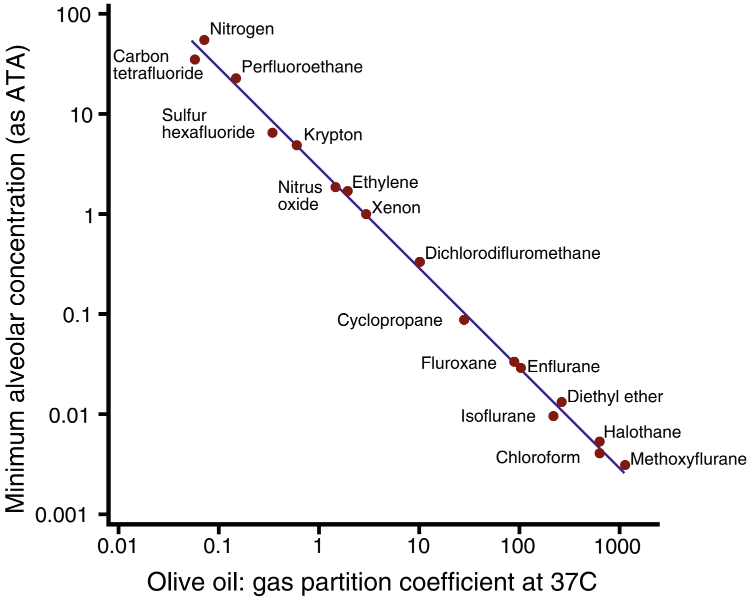

Fig. 4.5 The Meyer–Overton Hypothesis suggests the potency of a gas to produce anaesthesia is directly proportional to the fat solubility as measured by the relative solubility in fat and water—here quantified as the oil:gas partition coefficient. Note nitrogen is highly insoluble compared to useful anaesthetic gases, and so requires great pressures to exert anaesthesia. Only when breathing air at pressures above about 40 msw (5 ATA) are the effects notable. Initial concept from Crowder [29]

and most inert gases display this property—although there are great differences in the partial pressure (dose) required to achieve impairment in function. Xenon is anaesthetic at less than one ATA and is a useful anaesthetic gas in wide use in Europe, with a requirement of about 0.63 ATA (62.2 kPa) to achieve clinical anaesthesia [26]. Although estimates vary, the partial pressures required for other gases vary widely, with nitrogen requiring about 70 to 80 ATA to produce surgical anaesthesia (7,091 kPa to 8,104 kPa or more than 700 msw) [27]. Although recently questioned, the Meyer–Overton hypothesis is a useful concept and suggests the potency of any anaesthetic gas is directly proportional to the solubility in fat as measured using the olive oil-gas partition coefficient (Fig. 4.5). Nitrogen is quite insoluble in fat (low partition coefficient) and thus very high partial pressures are required to produce effect [28].

In practice, IGN from nitrogen is expressed as the insidious onset from about 40 metres depth (5 ATA) of a state of ‘euphoria, retardation of the higher mental processes and impaired neuromuscular coordination’, which is progressive with increasing pressure so that at 10 ATA (90 msw) most individuals will be unresponsive and in a state of stupefaction. Frank unconsciousness develops beyond that point. In 1939, Behnke and Yarbrough first reported that substitution of helium for the nitrogen in compressed air eliminates these effects [30]. Although there is marked individual variation in susceptibility to IGN, all divers breathing compressed air are significantly affected at a depth of 60–70 metres.

The higher functions, such as reasoning, judgement, recent memory, learning, concentration and attention are affected first. The diver may experience a feeling of well-being and stimulation similar to the overconfidence of mild alcoholic intoxication. Occasionally an individual will report the experience as terrifying and deeply unpleasant, and this is more probable in the novice who is apprehensive in her new environment. Deeper exposure is characterized by impairment of manual dexterity and progressive deterioration in mental performance, automatisms, idea fixation, hallucinations and finally, stupor and coma. Some divers complain of tunnel vision. They are less aware of potentially significant dangers outside their prescribed tasks (perceptual narrowing) [31]. More recently, abnormal emotional processing has been described, with a suggestion that the emotional responses to threat are muted with increasing IGN [32]. An approximate correlation between depth and both symptoms and signs is shown in Table 4.2.

The narcosis is rapidly evident on reaching the given depth (partial pressure) and is not progressive with time. It is more pronounced initially with rapid compression (descent) and is rapidly reversible upon reduction of the ambient pressure (ascent).

IGN is increased with stress and distraction from other sources including cold, reduced sensory input, and both oxygen and carbon dioxide intoxication. Frequent

Table 4.2 Some observations on the effects of exposure to compressed air at increasing pressure/depth [31]

Pressure (ATA)	Effects
2–4	Mild impairment of performance on unpractised tasks; mild euphoria
4	Reasoning and immediate memory affected more than motor coordination and choice reactions; delayed response to visual and auditory stimuli
4–6	Laughter and loquacity may be overcome by self-control; idea fixation, perceptual narrowing and overconfidence; calculation errors, memory impairment
6	Sleepiness, illusions, impaired judgement
6–8	Convivial group atmosphere: may be terror reaction in some; talkative; dizziness reported occasionally; uncontrolled laughter approaching hysteria in some
8	Severe impairment of intellectual performance; manual dexterity less affected
8–10	Gross delay in response to stimuli; diminished concentration; mental confusion
10	Stupefaction; severe impairment of practical activity and judgement; mental abnormalities and memory defects; deterioration in handwriting; uncontrollable euphoria, hyperexcitability; almost total loss of intellectual and perceptive faculties
> 10	Hallucinogenic experiences; unconsciousness

or prolonged exposure produces some acclimatization, but this may be due to a reduction in psychological stress rather than represent true adaption.

A reliable indication for the presence of IGN is not yet available. Such an indicator would be useful in predicting individual susceptibility (for diver selection); comparing the relative narcotic potencies of different respiratory diluents for oxygen; delineating the role of factors other than inert gas in producing depth intoxication and monitoring the degree of impairment during practical tasks.

4.3.4.2 Oxygen Toxicity

The normal partial pressure of oxygen (PO_2) in air is approximately 0.2 ATA. Although essential for survival, oxygen is toxic at an elevated partial pressure, and the complex systems we have for defending ourselves from oxygen toxicity is a testament to the evolutionary pressure to utilize this highly reactive molecule [33].

A high inspired pressure of oxygen (PiO_2) has several physiological effects on the body. While there is no direct effect on ventilation, there is a reduction in the CO_2 carrying capacity of haemoglobin, a vagally mediated bradycardia and vasoconstriction of intracranial and peripheral vessels. The many manifestations of oxygen toxicity are summarized in Fig. 4.6. In relation to diving, toxic effects on the central nervous system (CNS) and lungs are of prime importance and only these will be discussed in detail.

CNS toxicity (also referred to as the ‘Paul Bert effect’ after the French physiologist [7]) is an acute phenomenon with a threshold above a PiO_2 of about 1.5 ATA (5 msw) and displaying wide individual variability. Pulmonary effects (also referred to as the ‘Lorrain Smith effect’ after the Scottish pathologist) are more insidious in onset but are apparent at lower pressures with a threshold of about 0.55 ATA.

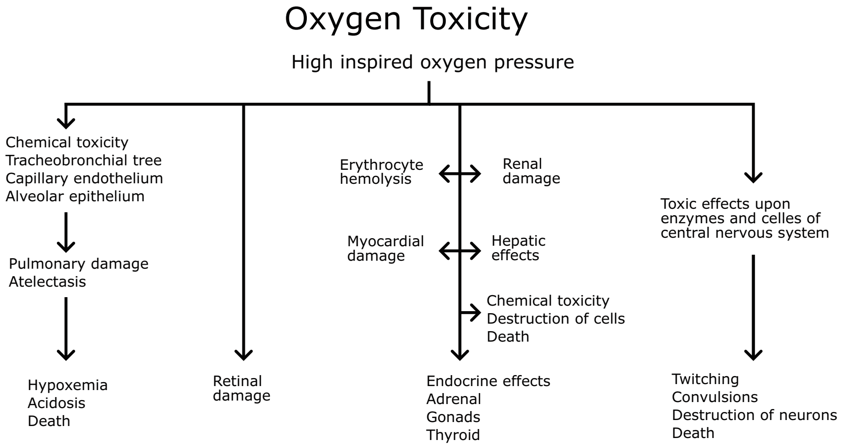

Fig. 4.6 Summary of major manifestations of oxygen toxicity

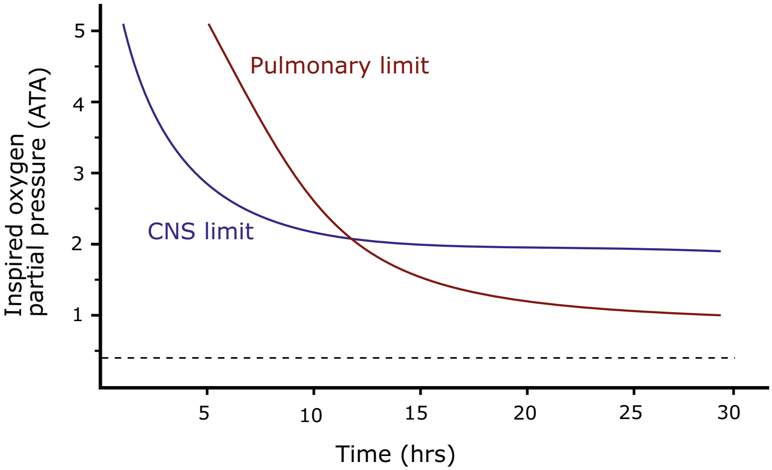

Fig. 4.7 Prediction of pulmonary and CNS toxicity

At lower pressures, pulmonary toxicity is the limiting factor regarding duration of exposure, whereas at higher pressures neurological toxicity is of prime concern, as indicated in Fig. 4.7.

The precise mechanism of oxygen toxicity is unknown. There are a great many sites at which oxygen acts on metabolic pathways or on specific cellular functions. These sites may involve cell membranes, ‘active transport’, synaptic transmission, mitochondrial or cell nuclei. Many enzymes are inactivated by high PO_2, particularly those containing sulphydryl groups (-SH). It is postulated that adjacent -SH groups are oxidized to form disulphide bridges (-S-S-) thus inactivating the enzyme (this may be important in the development of hyperoxic cataracts of the lens of the eye). Enzymes containing -SH groups, and known to be susceptible, include glyceraldehyde phosphate dehydrogenase (a key enzyme in glycolysis), the flavoprotein enzymes of the respiratory chain and the enzymes involved in oxidative phosphorylation.

The *oxygen free radical theory of toxicity* is widely accepted as an explanation at the molecular level [34]. The production of highly reactive free radicals is a normal consequence of aerobic metabolism, and for this reason, aerobic organisms have developed antioxidant mechanisms to cope with molecular oxygen exposure. Human cells have a system of enzymes to scavenge these radicals called the tissue antioxidant system. Two of these enzymes, superoxide dismutase and catalase, are involved in maintaining adequate supplies of reduced glutathione (containing sulphydryl groups) to deal with the free radicals.

In the face of hyperoxia these mechanisms may be overwhelmed leading to the formation of excess reactive oxygen species and direct cellular toxicity through enzyme inactivation and structural damage (e.g. lipid peroxidation). These radicals are intermediates formed in many biochemical enzyme-catalysed reactions and are

Table 4.3 Physiologic factors known to predispose to oxygen toxicity, from [33]

Physiological states:	*Gases*:
• Physical exercise • Hyperthermia • Immersion • Stress response	• Carbon dioxide • Nitrous oxide • Inert gases
Pathological states:	*Chemicals*:
• Fever • Congenital spherocytosis • Vitamin E deficiency	• Paraquat • NH_4CL
Drugs:	*Hormones and neurotransmitters*:
• Amphetamines • Acetazolamide • Aspirin • Atropine • Disulfiram • Guanethidine	• Insulin • Thyroxin • ACTH • Cortisol • Adrenaline, Noradrenaline • GABA
	Trace metals:
	• Iron • Copper

the result of the reduction of the oxygen molecule by electrons. For example, the superoxide anion O_2 is formed when oxygen accepts a single electron and hydrogen peroxide (H_2O_2) two electrons. The final reaction is the acceptance by oxygen of four electrons to form water or a stable hydroxyl anion. All these species of oxygen, referred to as oxygen radicals, are highly oxidative [33].

Many factors predispose to the development of oxygen toxicity, and these are summarized in Table 4.3. Several of them have in common the introduction of an added stressor (e.g. fever or exogenous adrenaline), while higher oxygen levels may be tolerated in the presence of enhancers of inhibitory pathways such as lithium (through increasing gamma-aminobutyric acid (GABA) levels).

Central Nervous System (CNS) Toxicity

In diving, CNS oxygen toxicity is the factor limiting depth when oxygen supplementation is used. While breathing compressed air, the effects of increased partial pressure of nitrogen (see Sect. 4.3.4.1) usually prevent the diver from reaching a depth and duration at which oxygen will become a problem. ‘Technical’ diving, in which a higher FiO_2 than air is commonly used, permits CNS toxicity.

The onset of toxicity may be sudden and develop without warning. A wide range of symptoms and signs has been described, the most dramatic of which is a generalized convulsion, similar to a grand mal epileptic seizure. In practice, only about half of those affected describe any premonitory symptoms. When present, such manifestations include nausea, vomiting, light-headedness, dizziness, tinnitus, dysphoria, tunnel vision and twitching.

An important aspect of toxicity is the great variation in susceptibility. As well as the wide range of tolerance between individuals, there is marked variation in an individual's tolerance from day to day [35]. In any diver, the time of onset of symptoms cannot be related to a predictable depth or time of exposure. Overall however, it is clear the greater the partial pressure and the longer the time exposure, the more likely is the toxicity to develop. The danger of convulsions prevents divers breathing 100% oxygen in safety when deeper than 8–10 msw.

Pulmonary Toxicity

Clinically obvious pulmonary oxygen toxicity does not manifest in short duration oxygen diving and is of importance only in saturation and long chamber dives and where high partial pressures of oxygen are inspired, such as during therapeutic recompression. Prolonged exposures to partial pressures as low as 0.55 ATA (such as in space flight) have been found to produce significant changes. A PiO_2 0.75 ATA has produced toxicity in 24 hours.

Pulmonary toxicity causes progressive respiratory distress leading to respiratory failure and finally death. In patients receiving high concentrations of oxygen therapeutically, it is sometimes difficult to distinguish between the conditions for which the oxygen is given and the effects of oxygen itself (e.g. shock lung, respiratory distress syndrome).

The factors affecting the degree of toxicity are the PiO_2, the duration of exposure and individual variation in susceptibility. When breathing 100% oxygen at 2.0 ATA, the typical time to produce symptoms in fit individuals is around three hours, but some individuals may remain symptom-free for up to eight hours.

The earliest symptom is usually mild tracheal irritation manifesting as retrosternal discomfort and aggravated by deep inspiration. There may be a dry cough. Chest tightness is often reported and with increasing exposure the discomfort will progress to significant retrosternal pain, dyspnoea at rest and uncontrollable cough. The higher the inspired oxygen pressure, the more rapidly symptoms develop and the greater the intensity. While there are usually no physical signs, some inspiratory extra sounds (rales) may be heard on deep inspiration and low grade fever may develop after prolonged exposure. Eventually, pulmonary infiltrates become increasingly prominent on chest X-ray and a typical adult respiratory distress pattern (ARDS) develops that may be irreversible and fatal.

Forced vital capacity (FVC or VC) is often used to monitor divers at risk and in order to detect early changes before distressing symptoms develop. Reduction in VS is usually progressive throughout the oxygen exposure and may occasionally take several days to return to normal. VC has been used to delineate pulmonary oxygen tolerance limits in normal subjects and the relationship between VC and exposure is shown in Fig. 4.8. Changes in diffusing capacity for carbon monoxide may be the most sensitive indicator of progress.

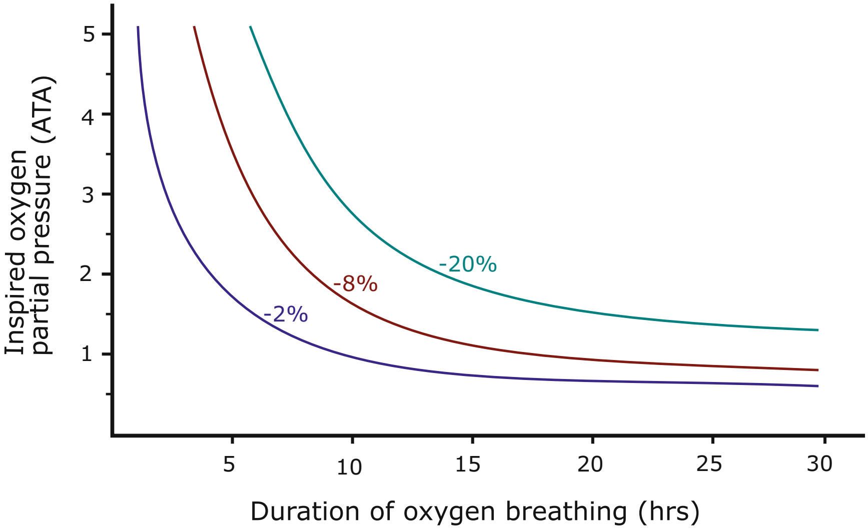

Fig. 4.8 Vital capacity (VC) changes with oxygen breathing, from [36]. Increasing inspired oxygen will hasten the toxic effects of oxygen. Breathing 1 ATA of oxygen for 10 hours will produce approximately a 2% decrement in VC, while breathing 3 ATA of oxygen for 10 hours will result in a more than 20% decrement

No specific therapy is available to delay or modify the pulmonary damage caused by hyperoxia. When toxicity is evident, the oxygen partial pressure should be reduced as soon as practically possible.

In order to assist in the prevention of significant pulmonary toxicity, one concept that has gained popularity is that of the 'UPTD' or unit of pulmonary toxic dose. Using UPTDs, different exposures in time and PiO_2 can be expressed as a 'standard' minutes of exposure at 1.0 ATA. Expected UPTDs can be calculated from any planned exposure and that exposure modified to keep the decrement in VC within acceptable limits (see Clarke [35] for a fuller explanation).

4.3.4.3 Carbon Dioxide Toxicity

Carbon dioxide (CO_2) is produced from the process of cellular respiration and needs to be eliminated via the lungs. Diving neither fundamentally alters the requirement of ventilation to adjust to maintain normal arterial carbon dioxide tension ($PaCO_2$), nor the rate of production. For a hypothetical resting diver the production of CO_2 will be the same except for any additional metabolic requirement for thermal regulation and increased work of breathing. At high work rates, increasing depth or when using breathing circuits with high resistance, there is potential for hypercarbia and the development of toxicity.

The normal $PaCO_2$ is about 40 mmHg and for mixed venous blood is about 46 mmHg. CO_2 in the alveolar gas ($PACO_2$) is in equilibrium with the pulmonary veins and is therefore also about 40 mmHg. Because CO_2 is the product of a metabolic process and we do not produce more of this gas simply because we are at depth, the $PACO_2$ is constant irrespective of depth, unlike oxygen and nitrogen that reflect the pressures in the inspired gas.

CO_2 (along with acidosis) is the primary stimulus for respiration at the central medullary chemoreceptors in the brain. About 200 ml of CO_2 are produced and excreted per minute at rest, but much larger amounts with exercise. As long as ventilation can increase in response, the arterial CO_2 tension will be maintained at a normal level and as a diver descends, the alveolar percentage will decrease.

Divers can manipulate the $PaCO_2$ in both directions. In breath-hold diving, deliberate hyperventilation prior to diving can drive down $PaCO_2$ and extend breath-hold time. For scuba divers, deliberate hypoventilation will allow $PaCO_2$ to rise in order to extend dive time through conservation of air. Both strategies are not without risk. Hyperventilation can allow a breath-hold diver to delay the breathing 'breakpoint' due to rising $PaCO_2$ at the risk of dangerous levels of hypoxia and potential unconsciousness and death prior to reaching the surface. The physiology of breath-hold diving is fascinating and further appraised in Sect. 4.3.7, and in [37].

A rising $PaCO_2$ has widespread effects on the body, most notably the respiratory, circulatory and nervous systems. Where high tissue CO_2 (hypercapnia) produces pathophysiological changes dangerous to the diver, the term '*CO_2 toxicity*' (or '*CO_2* poisoning') is used.

Excluding asphyxia and drowning, there are four main mechanisms of CO_2 toxicity in diving: failure of an absorbent system in closed or semi-closed rebreathing apparatus; inadequate ventilation (flush) of a diving helmet; inadequate pulmonary ventilation (often deliberate) or with increased resistance from the equipment. Whatever the cause, CO_2 toxicity is much more rapid when the diver is exercising and producing large amounts of CO_2.

Inadequate ventilation at extreme depths is a consequence of the combination of equipment resistance and increased gas density. Extreme reductions in ventilation and the increased work of breathing are one of the limiting conditions for achievable depths while immersed. With any given set of equipment there will come a point where the work of breathing dense gas produces more CO_2 than can be eliminated through the minute ventilation that can be achieved. The result is a rapid rise in alveolar, blood and tissue PCO_2 to the point of unconsciousness and death.

Under less extreme conditions the combination of tight wetsuits, harnesses and buoyancy compensators can also restrict thoracic movement and place an increased workload on the diver's respiratory muscles. The extent to which this load is overcome varies greatly among divers, but there is often some elevation of the alveolar PCO_2.

Clinical features depend on the rate of development and degree of CO_2 retention. They vary from mild compensated respiratory acidosis, detected only by blood gas and electrolyte estimations, to rapid unconsciousness and death with exposure to high $PiCO_2$ as a result of absorbent failure in a rebreather unit. As suggested above, a rising CO_2 is a powerful stimulant to respiration, such that a typical subject breathing air on the surface will double their minute volume when exposed to an inspiratory mixture containing 3% CO_2. There may be some subjective complaint of dyspnea (breathlessness), but at this level, no disturbance of central nervous system function. At a $PiCO_2$ of 5–6% dyspnea will become distressing and is accompanied by further increases in tidal volume and respiratory rate with increased arterial blood pressure and pulse rate. There is sweating of the forehead and hands, and the face feels flushed, bloated and warm. Eventually, mental confusion and lack of coordination may become apparent. At a $PiCO_2$ of around 10% these changes reverse, with a lower pulse rate, hypotension and severe mental impairment. Levels of around 12–14% will cause loss of consciousness and eventually death by central respiratory and cardiac depression. This corresponds with a $PACO_2$ greater than 150 mmHg at 1 ATA. Rapid onset of hypercapnia may be associated with midbrain convulsions, extensor spasms and death.

Removal from the toxic environment usually results in rapid recovery, although some divers complain of nausea, malaise or severe headache for several hours.

It is important to note the inspired concentrations required to produce these effects are progressively lower with increasing depth because toxicity depends on the partial pressure rather than inspired concentration. Breathing 5% CO_2 at 1 ATA delivers a PCO_2 of about 38 mmHg, while the equivalent figures at 2 ATA is 76 mmHg.

There are some divers who tolerate high PCO_2 levels with apparent ease—often called '*CO_2 retainer*s'—and this may be particularly so when breathing high oxygen mixtures that can blunt the response to rising CO_2. It is not clear to date whether the impaired response in these divers is inherent or acquired. It may be these divers progressively elevate their CO_2, as an alternative to increasing their ventilation, when the resistance to breathing increases. Under these conditions, it is theoretically possible that toxic levels may eventuate.

Conventional open-circuit equipment using air (scuba) is much less often associated with severe CO_2 retention. Many divers do, however, reduce their ventilation voluntarily in order to conserve air and allow mild elevations of their $PaCO_2$. This practice of long inspiratory and expiratory pauses that reduce minute ventilation is called '*skip breathing*' and often results in a throbbing frontal or bi-temporal headache at the end of a dive and which clears after surfacing. This practice is not generally advised, but common among relatively inexperienced divers trying to extend their dive time. A link with serious diving injury has not been established. It is possible divers develop an adaptation allowing them to tolerate higher levels of CO_2 while diving. Similarly, as 'skip breathers' continue to dive, this breathing pattern becomes habitual and a tolerance to CO_2 may develop.

High Pressure Neurological Syndrome (HPNS)

HPNS is a phenomenon seen with deep diving and usually associated with the use of helium in the place of nitrogen as a diluent for oxygen. As discussed above, high partial pressures of nitrogen cause disabling narcotic effects, but helium is a notably non-narcotic gas and is frequently used in deep diving to avoid narcosis.

HPNS has been described from depths of about 150 to 200 metres (16 to 21 ATA) and is a serious problem that grossly impairs normal neurological functioning and can be associated with unconsciousness and death if allowed to progress. It remains a major limitation to deep diving. Although there were some reports of unexplained neurological dysfunction in experimental animals for about 1880, the first reliable reports of HPNS in humans were made by multiple authors from Britain, Russia, the USA, and France in the 1960s as experimental teams investigated the limits on deeper dives for both commercial and military purposes [38]. The common feature was the use of helium–oxygen mixtures to avoid inert gas narcosis.

The most commonly reported symptoms are tremors (fine at first and becoming coarse), myoclonic jerking, mental clouding and the eventual development of generalized clonic seizures. Divers also report dizziness, headache, euphoria and drowsiness, but the symptoms are notoriously variable. If the pressure is further increased or maintained seizures will result in hypoxia due to the interruption of respiration and death. A reduction in the ambient pressure will relieve symptoms. The addition of a narcotic gas such as nitrogen, hydrogen or even nitrous oxide to the inspired gas mixture will significantly delay or mitigate these symptoms and can be used judiciously to allow further safe descent. For any given gas mixture, the longer the individual has to adapt to rising ambient pressure (slow descent), the less severe the symptoms. There is a marked inter-individual variation in susceptibility.

Gas breathing *per se* does not seem responsible for the development of HPNS and the phenomenon is more likely related to increased hydrostatic pressure. High pressures appear to deform cell wall structures and result in increased excitability in the central nervous system. It is postulated that the reversal of symptoms with narcotic agents (including the gases mentioned above) represents a restoration of normal cell wall function by physical reversal of the pressure changes within cell walls. There is much left to explain about HPNS, which remains an active area of investigation outside diving medicine because of the equally poorly explained phenomenon of the reversal of drug-induced narcosis by anaesthetic agents on the application of pressure [39].

For a more complete description of HPNS physiology including efforts to prevent and treat phenomenon, see Bennett [38].

4.3.5 Cardiovascular Physiology of Submersion

During immersion and diving scenarios, the cardiovascular system is subjected to a number of stresses that may alter cardiovascular functionality. These stresses include temperature, breath-hold diving, reflexes and exercise. Any of these stressors, alone or in combination, can have a significant impact on cardiovascular functions. It is considered that stresses can induce dysfunction in the absence of diseases. Minor cardiac conditions may preface major problems for divers, especially during underwater activities [46].

Stress related changes to cardiac function include tachycardia or bradycardia, hypertension, a reduction of blood volume secondary to submersion-induced diuresis and an overall increase in cardiac work.

Immersion counters the effect of gravity. Venous return is expedited from the vessels of the limbs, causing a redistribution of peripheral blood towards the central thorax, increasing intrathoracic blood volume by up to 700ml. The right atrial filling pressure is also increased by 18 mmHg [43]. Consequently, an increase in stroke volume and cardiac output occurs, due to the increased ventricular preload. Due to the increased cardiac output, the heart's workload is increased by over 30% [43]. This effect can be further intensified when immersed in cold waters. Negative pressure breathing also contributes to the diuretic effect of immersion.

Along with immersion comes a set of reflexes inducing cardiovascular changes. The initial diving response is associated with bradycardia and intense peripheral and selective visceral vasoconstriction. Face immersion exacerbates the haemodynamic effects induced by body immersion.

Over time, the haemodynamic response of the cardiovascular system to full immersion is a reduction in cardiac output, resulting from a decrease in both heart rate and stroke volume, and the reduction of blood volume following diuresis. The reduced blood volume is distributed mainly to the vital organs (heart and brain). The reflexes to immersion result in the effort to maintain blood pressure in a healthy range, reduce heat loss by reducing heat transfer to peripheral regions and by conservation of oxygen for vital organs.

Temperature changes during immersion also have a significant impact on the cardiovascular system, amplifying the previously noted cardiac responses to immersion. Initial cold water immersion causes an increase in sympathetic activity. These sympathetic activities are responsible for an increase in heart rate, systolic blood pressure and ventilation. Furthermore, cold water induces peripheral vasoconstriction that subsequently forces further centralization of blood volume and results in both diuresis and fluid volume reduction.

Exercise on land is commonly associated with an increased heart rate and cardiac output, which do not produce an elevation in blood pressure because muscles and skin become vasodilated. However, during diving vasodilatation is inhibited and thus heavy exercise causes an increased blood pressure and oxygen consumption underwater. Heavy exercise is also considered to aggravate any tendency to cardiac dysrhythmia during immersed conditions.

Heart rate variability (HRV) studies have confirmed a parasympathetic dominance with increased vagal activity and reduced sympathetic tone while diving [44, 45]. ECG abnormalities are frequent during or after the dive (T-wave inversion, premature ventricular excitation, atrial fibrillation) [43], which reflect an inhibition of vagal rhythm and interference with atrio-ventricular conduction.

More detailed information about cardiovascular physiology in diving can be found in Bennett [43].

4.3.6 Physiology of Drowning

Drowning is defined as the process of experiencing respiratory impairment from submersion in liquid [40]. It is the fourth most common cause of injury-related death, accounting for almost half a million deaths annually worldwide [41]. In drowning physiological impairing events are immersion (upper airway above water) and submersion (upper airway under water) [42].

During a drowning event, the victim is unable to ventilate the lungs, resulting in oxygen depletion and carbon dioxide retention. The victim becomes hypercarbic, hypoxemic, and acidotic and will often inhale water leading to death.

During the drowning process, both hypertonic (sea) and hypotonic (fresh) waters cause changes to pulmonary surfactant and the alveolocapillary barrier. These changes in alveolar surface tension and pulmonary compliance cause alveolar instability and atelectasis, negatively affecting the ventilation–perfusion ratio. Prevailing hydrostatic forces during drowning disrupt the integrity of alveolar-capillary membranes, leading to an incapacity for gas exchange. Furthermore, aspiration of either hypo- and hypertonic liquid causes a ventilation–perfusion shift, hypoxemia and metabolic acidosis. Subsequently, these are followed by myocardial depression, pulmonary vasoconstriction and changes in capillary permeability. Loss of consciousness while drowning is associated with asphyxia following liquid aspiration, loss of pulmonary oxygen uptake, brain energy failure and the deterioration of higher brain functions [42].

Although drowning constitutes the primary cause for diving fatalities, it needs to be understood that drowning often occurs as a consequence of other events leading to a reduced level of consciousness and the loss of upper airway reflexes.

4.3.7 Breath-Hold Diving

Breath-hold diving is the oldest form of diving and has been of great importance for commercial and military purposes. Nowadays, breath-hold diving is commonly a sporting activity, including spearfishing, underwater hockey and competitive freediving. For many years it was believed that depth was limited to approximately 30 m, as the lung gas volume diminished with increased depth (Boyle’s Law). At this depth, a critical point would be reached where lung tissue would rupture and pulmonary haemorrhage would occur. However, this is not the case, mainly because the human body is able to compensate for this effect by the onset of the diving reflex and shifts of blood volume into the thorax during breath-hold descent. More practically, duration of breath-hold diving in humans is limited by the body’s oxygen reserves. At the time of writing the record for breath-hold time on air is over 11 min, whilst the deepest recorded dive is over 200 m.

All diving mammals hold their breath, and their breath-hold time is limited by the amount of oxygen available in the body at the beginning of the dive. In humans, O_2

is mostly stored in the lungs, holding virtually all the oxygen required for the dive. During breath-hold diving O_2 is consumed and carbon dioxide, CO_2, is produced and enters the blood. In the absence of ventilation, the partial pressure of carbon dioxide (pCO_2) is constantly rising. Thus, the breath-hold length is determined by the time it takes for the blood pO_2 or pCO_2 to reach a critical level. The critical pCO_2 level triggers the respiratory system in the brain and immediately forces the diver to take a breath, while the critical pO_2 level will result in loss of consciousness. Either will result in drowning.

As the breath-holding diver descends, the increased ambient pressure squeezes the thorax and gases in the lungs and both, O_2 and N_2 diffuse down the concentration gradient into the blood and tissue. During ascent the chest and the gases in the lungs re-expand diluting any remaining O_2. As a result the blood partial oxygen pressure pO_2 falls more rapidly than would be expected from consumption alone. The diver is now subjected to a greater risk of losing consciousness from hypoxia when approaching the surface. This event is known as '*Shallow Water Blackout*'. The risk of blackout is amplified when the diver hyperventilates before starting the dive. Hyperventilation decreases the initial pCO_2 and allows an extended time to reach the critical pCO_2 limit (breakpoint) when the urge to breathe cannot be resisted. However, also allowing more time for pO_2 to drop at a dangerously low level (Fig. 4.9).

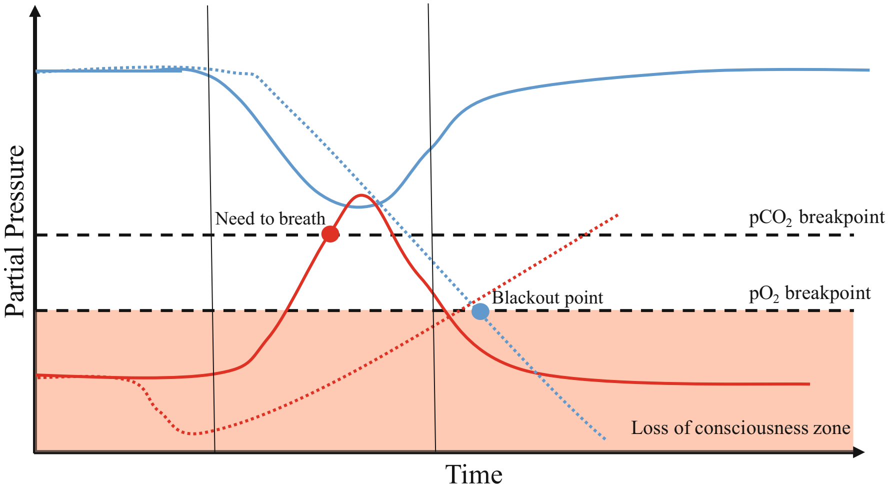

Fig. 4.9 While hyperventilating, the initial pCO_2 is reduced, to extend the time needed to reach the critical breaking point. Thus, pO_2 can continue to fall during this extended time, reaching a dangerously low level in the loss of consciousness zone. Blue lines display the pO_2 trend and red lines the pCO_2 trend. While full drawn lines indicate the trend during normal breathing and diving, the dotted lines represent the trend after initial hyperventilation. When prior dive normal breathing occurred, the pCO_2 breakpoint is reached before a critical low pO_2 can be reached. Hyperventilation shifts the pCO_2 breaking point and a black out scenario can occur

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Chapter 5
Decompression Modelling and Algorithm

Tobias Cibis

5.1 Decompression Illness and Decompression Sickness

Decompression illness (DCI), by definition, is initiated by a reduction in ambient environmental pressure. It most commonly occurs in compressed air divers, caisson workers, aviators and astronauts. During the decrease in ambient pressure, gas bubbles can be introduced into blood and bodily tissues [1]. These bubbles are responsible for the onset of physiological responses, which may lead to the clinical manifestation of DCI. For simplicity reasons at the beginning, bubble formation is the product of total diving duration, depth and ascent rate [2]. Detailed mechanisms of bubble kinetics are introduced later on in this chapter, but firstly, the medical consequences of DCI are investigated.

The introduction of bubbles during or after ascent from depth to the surface follows two mechanisms, which are distinguished by the occurrence of bubbles either in the arterial or venous system. Bubbles may enter the arterial blood stream pulmonary barotrauma if air is trapped inside the lungs, or through an existing patent foramen ovale (PFO) [2]. Air trapped in the lungs expands upon decompression and may damage respiratory tissue and thereby provide a direct pathway to the arterial system. Bubbles in the arterial system are also likely to enter the circulation to the brain where they can cause cerebral arterial gas embolism (CAGE).

In the venous blood stream and tissues, dissolved gas may be excited into bubble growth [2]. These bubbles can manifest themselves as venous gas embolism (VGE). This is usually referred to as decompression sickness (DCS).

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5.1.1 Pathological Consequences of Bubble Formation

Consequences of bubble formation can be found in multiple physiological systems. Usually, different systems are affected at the same time with varying severity. The most common systems affected are the blood, joints, spinal cord, brain and skin tissues [3]. Consequences can vary from mild discomfort, which may resolve within days without intervention, to severe permanent impairment or death. In the following, different physiological systems and their pathology are presented.

Intravascular bubbles commonly form in the venous circulatory system. The venous system operates on low pressure, which favours bubble growth, by providing slow flowing conditions. Venous bubbles will eventually travel through the respiratory circulation to the pulmonary capillary bed. The lungs, as a low pressure system and the large alveolar capillary bed, operates as a filter for incoming venous bubbles and removes most bubbles via exhalation. However, large bubbles or a great number of accumulated bubbles may overburden the lung's filter function and become symptomatic as pulmonary embolism. Symptoms usually occur within 30 min following a risky time-depth diving exposure. Divers suffering from pulmonary embolism may experience chest pain, cough, dyspnoea, which can resolve spontaneously, or in rare severe cases cause unconsciousness and death. Pulmonary decompression sickness, including pulmonary embolism, is often accompanied by other serious manifestations of decompression illness. The pulmonary "bubble-filter" can fail if large amounts of bubbles are present [1]. Filtering failure is amplified by pulmonary diseases where a venous to arterial shunt exists, after multiple compression–decompression exposures, or using asthmatic medication. Venous bubbles may also enter the arterial circulation through a patent foramen ovale. Any increase in pulmonary arteries pressure due to filtering activity can enhance bubble passing through PFOs. As soon as venous gas bubbles are able to pass the pulmonary circulation or a PFO, they effectively become arterial gas emboli.

Venous bubbles have multiple pathological effects. Modern advances have started to explore the effects of gas bubbles on inflammatory responses. It is known that vascular gas bubbles activate the complement, kinin and coagulation cascades [2]. However, the full effects and significance of these mechanisms are still unknown. It is considered that common DCS symptoms, such as headache, fatigue or malaise, originate from the activation of these inflammatory mediators. Further suggestions are that a combination of gas bubbles and coagulation can cause venous infarction of the spinal cord [1].

The most reported DCS symptom in divers is joint pain, which usually occurs after the completion of a dive. Some divers, however, have reported that they first noticed pain 24 to 48 h after diving. The exact location of bubble accumulation in joints has not been fully determined yet. It has been suggested that the bubbles form and remain trapped in one of the pain-sensitive structures in the joints.

Gas bubbles also tend to form in spinal cord tissues [4]. Symptoms of spinal cord DCS can vary from mild, such as tingling sensations and mild paraesthesia, to severe with permanent paralysis. Common symptoms for mild to moderate severity are numbness, weakness, ataxia and bowel dysfunction, which usually onset over the duration of one to two days after diving. Severe cases mostly present 30 min after surfacing. In addition to DCS in spinal cord, the disease may also have negative consequences on peripheral nerves. Nerve involvement is displayed in sensory derangements and motor dysfunction.

Critical harm of DCS manifestation is usually caused in the brain [2]. Formation of bubbles within brain tissues were observed in animal studies; however, the process of manifestation in humans remains poorly understood. It is thought that the highly perfused brain tissue is more resistant to supersaturation, which minimizes the risk of bubble formation. Cerebral pathologies of DCI are usually attributed to vascular events, and most decompression injuries to the brain are considered to be the result of bubbles entering the arterial circulation and CAGE.

In the skin, gas bubbles persist in subcutaneous tissue and may cause transient pruritus or hyperaesthesia. Rashes on the skin can become visible [1, 3]. A more severe manifestation of DCS in skin is referred to as cutis marmorata, which presents as a red–purple mottling of the skin. This form of DCS often precedes more harmful symptoms and indicates the need for rapid medical intervention. It is also reported that bubbles can grow in and obstruct the lymphatic system causing swelling and discomfort.

After diving some divers may experience a combination of nausea, vomiting, vertigo and hearing loss [5]. These symptoms are likely the result of traumatic injury or DCS to the inner ear [6]. Inner ear DCS is associated with dives that are considered to accumulate a large amount of dissolved gas loads, especially in the scope of deep diving while using different gas mixtures (helium–oxygen, or nitrogen–oxygen mixtures) [5, 6]. Symptoms of the inner ear are usually accompanied by other gas bubble-induced diseases.

5.1.2 Risk Factors for DCI

The manifestation of any kind of decompression illness or decompression sickness is often associated with risk factors, which may increase an individual's susceptibility to develop the disease. It is important to be aware of these risk factors and it should be the goal of every diver to minimize all risks as much as possible. These risk factors can be divided into three categories: those related to the diver, those associated with the dive itself, and those connected to the post-dive period [1–6]. All three categories comprise several factors, which are briefly presented in Table 5.1.

Table 5.1 Risk factors that are associated with predispose a diver to DCI. Risk factors are divided into three categories: the diver, the dive and post-dive [1–6]

Risk factor	Description
The diver	
Body fat	Inert gas nitrogen is more soluble in lipid than aqueous tissues. Thus, a higher body fat percentage means greater risk for DCS, as a larger amount of bubbles can form in fatty tissue. Recent studies have failed to show a relationship between body fat or BMI and DCS
Age	Older divers tend to be more prone to develop DCS. This is usually considered due to a general decline in physical fitness and ability to resist adversity
Physical fitness	Studies have shown that strategic exercise prior to a dive may strengthen the resistance to DCI. The mechanisms responsible for protection are not fully understood. However, it is suggested that modulation in endothelial functionality and nitric oxide levels contribute to the resistance mechanisms. Good physical fitness should be maintained by every diver
Being female	Women could be at higher risk of DCS than men. Bubble growth may be promoted due to hormonal changes during menstruation, which can result in fluid microslugging, fluid retention, or slowing of circulation. Theoretically all these effects predispose women to a higher risk. However, surveys and studies have been inconclusive and contradictive and state that for diving any differences between women and men are trivial
Dehydration	Dehydration causes blood to "thicken" and decreases flow velocity through smaller blood vessels, which provides a condition favourable for bubble formation. It is probably appropriate to encourage divers to actively maintain good dehydration
Previous DCS	Having suffered from a previous episode of DCS may predispose an individual to another DCS manifestation. If the recovery from a previous DCI is incomplete, the risk to develop another episode is considered unacceptably high
The dive	
Repetitive diving	All activities that result in multiple surfacing, such as repetitive dives, multi-day dives and multiple surface ascents during a single dive are considered to increase the risk of DCS. The theoretical basis is that bubbles accumulate by the first ascent to the surface and are then excited to grow into larger, more harmful bubbles during any follow-up dive
Deep diving	Data collection from military divers suggest that deeper dives pose a greater risk for DCS. These depths are usually reached in commercial and military diving, and not so much in recreational activities
Heavy exercise	Exercise while diving accelerates absorption of inert gas, especially in those tissues whose perfusion is increased during heavy workloads. In both humans and animals, moderate and heavy exercises result in an increase of decompression requirements. Exercise is one of the undisputed risk factors for DCS. However, mild exercise increases peripheral blood flow and thereby can enhance the wash out of inert gas

(continued)

Table 5.1 (continued)

Risk factor	Description
Cold	The critical effect of cold is that the diver's body changes in temperature. This temperature change counteracts perfusion and gas elimination and, thus, is considered to contribute to the onset of DCS once divers get too cold
Post dive	
Exercise	Post-dive exercise, especially heavy lifting, is considered to increase both the likelihood of onset and severity of DCS. The underlying mechanisms of the negative impact of exercise are not fully understood
Rewarming	Rewarming of peripheral tissues too quickly (e.g. Jumping under a steamy shower) may promote bubble growth in such. Inert gas' solubility is decreased when temperature in tissues rises
Altitude exposure	Ascent to altitude after a dive translates to continued decompression mechanisms inside the diver's body. Bubbles are further excited into formation and growth. Diving agencies recommend avoiding air travel up to 12 h after a single no-decompression dive, and longer if repetitive diving was practiced

5.2 Gas Kinetics: The Bubble Formation Mechanisms During Decompression

The fundamental mechanisms of decompression are associated with the behaviour of gas bubbles, which are excited into bubble growth upon a reduction in ambient pressure, or ascent to the surface. The two main factors on nitrogen accumulation while diving are the depth and the time at depth [7–10].

While being submersed, a diver is supplied with compressed breathing air. The self-contained breathing apparatus provides the breathing air with ambient pressure. The deeper the diver ventures, the greater the ambient pressure rises, and the greater the partial pressures of the gas fractions in the air breathed. According to Henry's law, gas will dissolve into solution as the partial pressure of the gas increases. In diving, bubbles form from excess nitrogen (N_2) accumulation. Nitrogen is an inert gas, which is not metabolized in the human body [9, 10]. Unlike oxygen, which is consumed for physiological needs and thus is not accumulated in tissue or blood during an open water dive. Decompression from here on will be discussed with a sole focus on nitrogen.

During a dive, the breathing air at depth will be provided at ambient pressure. Alveolar nitrogen partial pressure thereby changes in the same dimension as changes in ambient pressure occur. A change in alveolar nitrogen partial pressure will establish a pressure gradient between the lungs, blood and body tissue, along which the inert gas will be transported. After a while, the pressure gradient diminishes as the partial pressures in tissues will change proportionally with the changes in the lungs and both will eventually equilibrate. Nitrogen partial pressures are now in equilibrium with the ambient pressure (Fig. 5.1), [10].

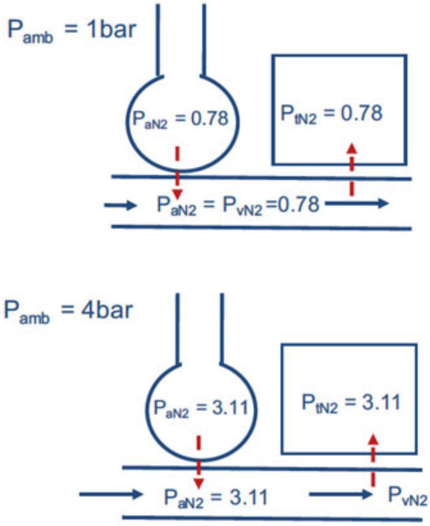

Fig. 5.1 **Top:** Alveolar, arterial and tissue nitrogen partial pressures are in equilibrium at 1ATA ambient pressure, which corresponds to terrestrial sea-level condition. **Bottom**: Partial pressures of alveolar, arterial and tissue nitrogen are in equilibrium at a new level, at 4ATA or 30m water depth. The partial nitrogen pressure has risen in the same dimension as the ambient pressure (Boyle's law). At this level, due to the effects of Henry's law, nitrogen will dissolve into solution

During the stay at depth, nitrogen gas will behave according to Henry's law and will dissolve into solution. The deeper the dive, the more nitrogen will dissolve into tissues and blood. Once the equilibrium is established, blood and tissues will be "saturated" [9, 10]. This can be expressed as:

$$\left(\sum P_{tis,\mathrm{N}_2} + P_{tis,\mathrm{O}_2} + P_{tis,\mathrm{CO}_2} + P_{\mathrm{H}_2\mathrm{O}}\right) = P_{amb}, \tag{5.1}$$

where P_{N_2}, P_{O_2}, P_{CO_2} denote the partial pressures of the individual gases in inspiration gases nitrogen, oxygen and carbon dioxide, respectively. $P_{\mathrm{H}_2\mathrm{O}}$ is the water vapour pressure at tissue temperature and P_{amb} the total ambient pressure. Furthermore, Pj describes the physiological location of the partial pressure, including j = [alv, art, ven, tis], for the partial pressures in the alveolars, arterial blood, venous blood and tissues, respectively [10].

Blood saturates very quickly, while other tissues saturate at different rates, which are dependent on the perfusion and the solubility of nitrogen in these tissues. Thus, well-perfused tissues saturate more quickly than poorly perfused, or aqueous tissues. The accumulation of nitrogen is influenced by the depth, which dictates the pressure gradient and level of saturation, and the time at depth, allowing the duration for different tissues to become saturated. The result will be an increase in the sum of dissolved gas partial pressures, when compared to surface condition (Fig. 5.1). The diver has accumulated dissolved inert gas in different amounts in multiple tissues proportionally to the tissues' solubility and perfusion. Risk factors (see Table 5.1) that influence tissue perfusion are likely to exacerbate nitrogen accumulation [10, 21].

Once the dive at depth is completed, the diver will start to ascent to the surface and experiences a decrease in ambient pressure. With the decrease in ambient

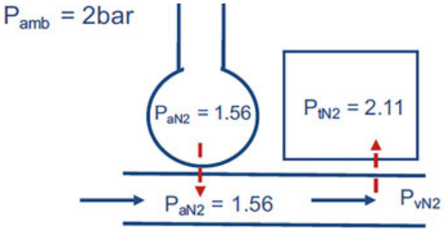

Fig. 5.2 During ascent, the partial inert gas pressures in alveolars and arterial system adapt more rapidly to the changing ambient pressure. The partial pressure of inert gas in the tissues requires a longer off-gassing time. In result, the P_{tis,N_2} partial pressure is greater than the ambient pressure. This state is referred to as "supersaturation", the fundamental condition for bubble formation

pressure, a reverse pressure gradient from the tissues to the lungs is developed for nitrogen off-gassing. The pressure gradient forces nitrogen to diffuse from tissues into venous blood and then to the alveoli where the inert gas is eliminated via expiration. However, nitrogen off-gassing does not occur in proportion to the reduction in ambient pressure, as diffusion from the tissue is a slower process. The slow nitrogen elimination from some tissues and blood can cause a condition during which the sum of gas partial pressures, predominantly from nitrogen, exceed ambient pressure. This can be expressed in an unequal equation:

$$\left(\sum P_{tis,\mathrm{N}_2} + P_{tis,\mathrm{O}_2} + P_{tis,\mathrm{CO}_2} + P_{\mathrm{H_2O}}\right) - P_{amb} > 0. \tag{5.2}$$

The tissue and blood are now "supersaturated"; see Fig. 5.2, [10].

Supersaturation is considered to inevitably promote bubble formation. A rapid ascent to the surface provides less time for the elimination of nitrogen through expiration, which likely causes a greater supersaturation and the formation of symptomatic bubbles. Studies have shown by employing Doppler ultrasound devices that venous gas bubbles appear upon most decompression. These bubbles may not end up causing DCI and a diver can remain asymptomatic [2, 3, 10]. The exact science of bubble formation, with the determination of its location of origin and mechanisms remains something of a mystery. Most appropriate explanations are derived from the physics of bubble kinetics. Considering the surface tension of a bubble's gas–liquid interface, the pressure inside the bubble relative to the surrounding pressure forces the surface tension to increase. The force exerted by the surface tension is thereby inversely proportional to the radius of the bubble. This means that with a decrease in ambient pressure, small bubbles tend to crush themselves. A spherical bubble, described by the inner bubble pressure P_{bub}, of radius, r, is the sum of all gas partial pressures inside of the bubble.

The sum of all gas partial pressures inside a spherical bubble (P_{bub}) of radius r is given by:

$$P_{bub} = P_{amb} + \frac{2\gamma}{r} + M. \tag{5.3}$$

The force across the gas–liquid interface is represented by the term $2\gamma/r$ and depends on the acting surface tension of the gas bubble [10, 19]. M depicts the additional pressure exerted from tissue displacement. The displacement pressure is usually small and for the purpose of the following discussion can be ignored. When the pressures inside the bubble and the surrounding are equal ($P_{bub} = P_{amb}$), a critical radius for the bubble can be found:

$$r \geq \frac{2\gamma}{\sum P_{tis,j} - P_{amb}} \tag{5.4}$$

During ambient pressure reduction, bubbles whose size exceeds the critical radius are expected to persist and grow, with dissolved inert gas from the surrounding diffusing into the bubble. Bubbles with smaller size than the critical radius will shrink and be crushed. Once a bubble persists, gas in solution will diffuse into the bubble at a rate that is determined by the pressure gradients across the bubble's surface layer. This gas transfer is described by Fick's first law:

$$\frac{d\,(P_{bub}\,V_{bub})}{dt} = A \sum \left(\alpha_{tis,j}\, D_j\, \frac{d\,P_{tis,j}}{dr} \right), \tag{5.5}$$

where V_{bub} and P_{bub} are the volume and the pressure of the total gas mixture inside the bubble, D_j and α_{tis} are the bulk diffusivity and solubility of the gas j in the tissue and A the bubble surface area. The gas partial pressure gradient $\frac{d(P_{bub}\,V_{bub})}{dt}$ describes the force across the bubble surface. The forces to create de novo bubble initiations are still not fully understood. Modern theories of bubble formation consider that microscopic gas nuclei pre-exist and that those act as seeds for bubble formation during supersaturation.

5.2.1 Tissue Gas Kinetics

In the previous section the physical mechanisms of gas kinetics during decompression are described. However, further mechanisms need to be considered to assess the development of decompression sickness. One relevant aspect is in the physiological exchange of gasses. The partial pressure exchange between blood and tissue is described by the concept of a tissue compartment model. The rate at which the tissue compartment partial pressure changes is thereby denoted as [10]:

$$\frac{dP_{tis}}{dt} = \frac{(P_{ai} - P_{tis})}{T} - \frac{1}{(V_{tis}\,\alpha_{tis})}\frac{d\,(P_{bub}\,V_{bub})}{dt}. \tag{5.6}$$

The first term of the left hand side ($P_a - P_{tis}$) describes the gas exchange by the partial pressure difference between arterial blood and the tissue compartment, while the second term accounts for the gas diffusion between tissue and an existing bubble inside this tissue. If no bubble exists, this term becomes zero [10].

5.3 Decompression Modelling

The fundamental idea of decompression modelling is to predict the dynamic behaviour of gas kinetics in order to prevent the onset of decompression illness [12]. The prevailing prevention concept is to control the reduction in ambient pressure (ascent rate) and to schedule decompression stops by interrupting ascent to provide sufficient time for tissue nitrogen off-gassing. These decompression stops are usually performed under conditions of limited tissue supersaturation to accelerate the nitrogen wash-out.

5.3.1 Diving Tables and Computers

Generally, every recreational diver has been educated on the principles of "no decompression" diving. These dives are performed in a fashion that decompression stops are not required, and no limits of bottom time are exceeded. The limits were determined empirically through experiments and adjusted according to diving outcomes. All bottom times and corresponding no-decompression limits are usually listed in the so called diving tables [13, 15] or modern diving computers [11, 14]. More experienced divers perform more challenging dives and are often employed for commercial or military diving, preform dives that require decompression and multiple stops at different depths. These decompression schedules are often planed in advance to the dive and then employed on diving computers.

5.3.2 The Scope and Complexity of Decompression Modelling

Decompression modelling is often the intent to describe, utilize and bring together a large number of different systems, in order to address phenomena that are the result of changes in ambient pressure. General decompression modelling can comprise a few hundred different parameters and variables and the same amount of equations to solve the mathematical problems at hand [9, 21]. Just to mention a few, common concepts accounted for in modelling comprise gas exchange, bubble formation vs. elimination in blood and tissue due to compression–decompression. These concepts are subjected to various properties such as diffusion, perfusion, phase separation, nucleation, equilibration, fluid shifts and a combination thereof (Table 5.2).

Table 5.2 Some terms and physical concepts including their description commonly used by researchers in decompression modelling. These terms present the fundamental stages of biology, physics and chemistry, which need to be accounted for while modelling decompression and bubble behaviour [21, 22]

Biophysical property	Description
Diffusion	Physical process where molecules of a material transfer from an area of high concentration to an area of low concentration. Usually occurs in a solution in gas or liquid
Perfusion	Rate of a liquid that flows through an object (e.g. blood flow through a vessel or tissue compartment)
Phase separation	Conversion of a single-phase system into multiple phase systems (e.g. separation of a solution into two immiscible solutions)
Equilibration	Process that will lead to the balance of two systems
Surface tension	It is the intermolecular force holding molecules on a surface layer together, preventing the formation of large holes in a liquid. It causes the layer to behave as an elastic sheet

Many more challenges come with the complexity of the functionality of biological systems, and diversity of interfaces and boundary conditions. While effects of pressure changes are usually quantified in physics, chemistry and engineering, the biology and medicine due to pressure changes in living organisms are much more complicated, and even more difficult to study on living subjects [21].

Given the large diversity and immense complexity in decompression science and modelling, it is difficult to cover everything in detail in one book, let alone in a chapter. Rather, the following content is considered to broadly introduce different approaches and application of decompression modelling and algorithms. For extended interest and reading experience, further references will be included.

5.4 Decompression Algorithm

Decompression algorithms are usually implemented on dive computers to calculate decompression schedules by controlling ambient pressure reduction rates. These algorithms are designed to incorporate real-time depth measurements, diving time and breathing gas composition [9, 10]. Most diving algorithms are derived from decompression modelling concepts and mathematically manipulate decompression tables for individual dives. The fundamental concepts focus on the prediction of bubble formation and/or the modulation of tissue gas uptake and elimination. Two different approaches are predominantly applied in diving for safe return to the surface: the gas content models and the bubble models [10]. Gas content models try to maximize tissue supersaturation to safe limits to accelerate inert gas elimination. These limits are derived by experiments and adjusted based on diving outcomes. Bubble models tend to limit tissue supersaturation early in the ascent to minimize bubble formation and growth according to prediction models of bubble behaviour [10]. In the following the most common algorithms for both models are presented.

5.4.1 Gas Content Decompression Algorithms

Gas content algorithms assess the uptake and elimination of inert gas into tissue compartments and schedule decompression with timely limited supersaturation conditions to maximize nitrogen elimination. The concept of various tissue compartments was first introduced by J.S. Haldane and colleagues [12]. From their studies in compressed air environments, they concluded that different tissue compartments become saturated with nitrogen at different rates. The rate of each compartment is governed by their perfusion and solubility coefficients. Thus, compartments are organized in parallel to arterial blood circulation and are categorized by their perfusion limitations. Equilibrium rates for all compartments are usually represented in half-time $[ln(2) \cdot time\,constant]$. Haldane initially proposed five tissue compartments with half-time of 5, 10, 20, 40 and 75 min [12]. Decompression schedules calculated by the gas content algorithms try to pull the diver into limited durations of supersaturation, which are still considered as relatively safe. The idea is to maximize the pressure gradient between tissues and alveolars by tissue supersaturation to accelerate nitrogen elimination from the tissue compartments. The most common algorithms, which are presented next, are those introduced by Robert Workman [15] and Buehlmann [16].

5.4.1.1 M-Value Decompression Algorithm

M-values are defined as the maximum value of inert gas partial pressure that the theoretical tissue compartment can tolerate without the manifestation of decompression illness symptoms. Thus, M-values are used to determine limits for gradients between tissue inert gas pressure and ambient pressure (both in absolute values), which are physiologically tolerable but also favourable for nitrogen elimination. Each tissue compartment is represented by one corresponding M-value [17, 18]. The algorithm, incorporating these M-values, is designed as a linear function of depth, and thus pressure. A linear relationship of the gradient behaviour was found to be accurate when compared to real-life study data. Given the linearity, the algorithm is characterized by having a slope parameter, which determines the changes in M-

values in correspondence to the change in ambient pressure. The slope parameter further depends on the tissue compartment's half-time, with faster half-times corresponding in a greater slope. Translated into physiology behaviour, this means that faster compartments tolerate a greater supersaturation than compartments with slower half-times [17, 18]. The M-value decompression algorithm attempts to pull the diver as close to the surface as possible for decompression, to establish the largest, safe, pressure gradient.

Workman's M-Value

The concept of M-values was significantly marked by Robert Workman [15] and his research in decompression for the US Navy. He established a linear relationship between tolerated tissue inert gas pressure and depth pressure:

$$M = \Delta M\, d + M_0, \tag{5.7}$$

$$d = P_{amb} - P_0. \tag{5.8}$$

The parameter of interest in this equation is "M", which is the relationship between tissue and ambient inert gas pressure. For ideal decompression scheduling, a critical threshold of "M", representing the toleration limit, should not be exceeded. The constant, M_0, denotes the tissue inert gas intercept pressure at sea level, also known as surfacing M-value. The depth, d, is measured in pressure units beginning at a reference pressure P_0 at sea level. ΔM is the slope of the linear M-value line and is evaluated for the change of tolerated inert gas pressure per unit depth. Thereby, the slope will change according to the half-time of the tissue compartment.

Buehlmann's M-Value

Buehlmann [16] followed the same linear relationship concept for decompression scheduling as Workman did. Tolerated inert gas pressure in theoretical tissue compartments is in a linear relationship to changes in ambient pressure.

$$P_{tol} = \frac{P_{amb}}{b} + a. \tag{5.9}$$

Similar to Workman, Ptol (= M) represents the tolerated inert gas pressure in the tissue compartments with critical values, which should not be exceeded during decompression. The reciprocal representation of the slope is denoted as b and corresponds to Workman as (b = $1/\Delta M$). The intercept value, a, is set in Buehlmann's algorithm to zero ambient pressure absolute.

The major difference between Buehlmann's and Workman's approach is the representation of the M-value. While Workman's values are based on depth pressure with a reference point at sea level (surfacing) pressure, Buehlmann's M-values are represented in absolute pressure. Buehlmann's approach comes with the benefit that it can be applied to diving in altitude. This came naturally, as Buehlmann was conducting his research in the Swiss Alps. The algorithm is commonly known as "ZH-L16", with "ZH" representing the research location "Zuerich", "L" denoting "linear", and 16 for the number of different tissue compartments utilized in this algorithm [16].

M-values do not represent hard decompression limits. Divers often misinterpret that staying within the M-value limits is completely safe [17]. There is still a likelihood for divers to develop DCS symptoms while staying well within the decompression limits, and there are divers who will not suffer from any DCS effects although breaching the limits. Every diver and each individual dive performed is different. The diversity in human physiology, risk factors that may predispose an individual to DCS and the variety of environmental factors, all of which cannot fully be accounted for in the M-value algorithm [10, 17, 18, 21].

5.4.2 Bubble Dynamic Decompression Algorithm

Decompression scheduling based on bubble behaviour intends to limit tissue saturation early in the ascent process to minimize bubble formation and growth. Bubble decompression algorithms utilize features of bubble dynamics and kinetics, following the assumption that bubbles are the leading cause for decompression sickness [10]. There are two basic strategies to assess bubble kinetics for decompression procedures. One strategy is to calculate the size of bubbles by employing equations to predict gas diffusion between gas bubbles and the surrounding tissues. The second strategy intends to predict the number of bubbles excited into growth during decompression. Two common examples that are introduced in the following are the Varying Permeability Model (VPM) [19] and the Reduced Gradient Bubble Model (RGBM) [21].

5.4.2.1 Varying Permeability Model

The Varying Permeability Model (VPM) was first introduced by Yount and colleagues [19] and is based on studies of bubble formation performed in a laboratory setting [20]. Their research work focused on bubble kinetics and how it can be applied for safe decompression scheduling. One important concept that was incorporated in their work is the surface tension of gas bubbles, especially with a gas–liquid layer. Surface tension is caused by the attraction of liquid molecules between each other due to various intermolecular forces and causes this layer of molecules to behave like an elastic sheet. The surface tension of bubbles that are immersed in liquid, attempts to minimize the bubble's surface area. Thus, these bubbles tend to shrink, as the surface tension directs the layer molecules towards the bubble's centre. However, as a consequence of this mechanism, the bubble's internal volume decreases, which subsequently causes the internal bubble pressure to increase. The shrinking process and counteracting rise in internal pressure eventually equilibrate. The internal pressure then compensates the forces excreted by surface tension and ambient pressure. This state is commonly expressed as the

Laplacian equation [19]:

$$P_{bub} = P_{amb} + \frac{2\gamma}{r} + M. \tag{5.10}$$

This equation shows that the bubble's internal pressure is greater than the ambient pressure by an additional factor depending on the bubble's radius r, and the surface tension γ. From his bubble studies in gel, Yount proposed that gas bubbles possess additional surface-active molecules in the surface layer called surfactants [19, 20]. These surfactants generate a force that opposes the surface tension, Phi and the surface pressure $2\gamma/r$ of the ambient pressure. It is considered that the surfactants have a stabilizing effect for the bubbles. Equation (5.10) can now be denoted with the additional force of the surfactants:

$$P_{bub} + \frac{2\Gamma}{r} = P_{amb} + \frac{2\gamma}{r}. \tag{5.11}$$

Next, Yount applied a "critical-volume hypothesis" assuming bubbles will be excited into growth, once the total volume of the dissolved gas exceeds a pre-defined critical volume, V_{crit}. The supersaturated state is expressed as P_{ss}. It was assumed that the body can deal with a certain amount of gas bubbles, N_{safe}. There, it is suggested that this is the amount of venous bubbles the lung is able to eliminate via expiration at any given time. Furthermore, it is expected that during decompression the actual number of bubbles, N_{actual}, is temporarily allowed to exceed the amount considered safe, N_{safe}, during supersaturation. Thereby, the rate at which the gas phase inflates is considered to be proportional to $P_{ss}(t) \cdot (N_{actual} - N_{safe})$. Yount denoted the decompression criterion as:

$$\alpha V_{crit} = \left(N_{actual} - N_{safe}\right) \int_0^{t_{max}} P_{ss}(t)dt, \tag{5.12}$$

where $(N_{actual} - N_{safe})$ are the constant bubble population initially determined at the first decompression stop, a, a proportionality constant, V_{crit} the critical gas phase volume and t_{max} the time at which the integral reaches its maximum. Thus, the criterion expresses that allowed supersaturation equates, if maintained throughout the entire ascent process, in the target value below the critical volume and bubble population. Hence, the general decompression strategy of VPM can be summarized as following: during descent the amount of gas dissolved into tissue and blood and changes in bubble radius are tracked. While ascending, the internal bubble pressure is continuously calculated. As bubbles are considered to grow if tissue supersaturation pressure P_{ss} exceeds the bubble pressure, ascent will be limited and divers forced to stop, once the supersaturation pressure is about to exceed the bubbles internal pressure [18–20].

5.4.2.2 Reduced Gradient Bubble Model

The Reduced Gradient Bubble Model (RGBM) approach employs a phase volume constraint across a total dive profile [21, 22]. The phase-volume constraint equation is rewritten in terms of a phase function, varying in time:

$$\int_0^{\tau} \frac{\partial \phi}{\partial t} dt \leq \Phi. \tag{5.13}$$

The model is parameterized by biological, chemical and physical factors. Bubbles are assumed to expand and contract during the dive. The material properties of these bubbles dictate the response to pressure changes, gas diffusion and excitation into growth. The estimation of the volume constraint is defined in terms of a bubble phase function (Φ), dependent on the number of gas bubbles predicted to be stimulated into growth by decompression, a supersaturation gradient, seed diffusion and Bolye's expansion–contraction law.

$$\frac{\partial \phi}{\partial t} = \left[\frac{\partial V}{\partial t}\right]_{diffusion} + \left[\frac{\partial V}{\partial t}\right]_{Boyle} + \left[\frac{\partial V}{\partial t}\right]_{excitation}. \tag{5.14}$$

The RGBM stages decompression iteratively ensuring that Phi does not exceed the predefined limitations.

Staging in RGBM requires the supersaturation gradient to remain under the seed-average bubble surface tension pressure:

$$\Pi - P \leq \beta \cdot e^{(\beta \epsilon)} \int_{\epsilon}^{\infty} e^{(-\beta r)} \cdot \frac{2\gamma}{r} dr. \tag{5.15}$$

More detailed information about the RGBM model can be found here [21, 22].

5.5 Modern Decompression Research

Modern research approaches into decompression science focus on the efforts to individualize any decompression scheduling and adjust limits towards physiological needs.

One approach intends to use continuous heart rate monitoring to calculate customized decompression schedules. The heart rate was assumed responsive to cardiac workload and to provide information on the blood flow to bodily tissues, and subsequent tissue perfusion rates. Thus, changes in heart rate would entail changes in perfusion impacting the rate of uptake and elimination of inert gas [23–26].

Decompression remains a science with unanswered questions. It has come a long way and each new development and progress was able to minimize the risk of decompression illness. However, any risk can never be fully ruled out.

A new path of research into decompression illness and the effects of Scuba and free diving is dedicated to analysis approaches involving biomarkers and gene expressions [27, 28]. Scuba diving including all the effects on the human physiology as well as the consequences of bubble formation are believed to provoke adjustments in biological pathways and genetic and/or hormonal cycles [28]. Thus, multiple studies start to collect data from blood samples prior- and post-dive to assess biological markers. Common markers that are utilized are those indicating any involvements of nitric oxide and anti-inflammatory processes [27], endothelial functions [29, 30], or those representing the cardiovascular and vascular systems [31].

Although these studies are still at the beginning, it is suggested that assessing biomarkers may also provide an insight into adaptation processes for scuba diving [32].

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Chapter 6
Biomedical Monitoring in Underwater Environments

Tobias Cibis, Stefan Gradl, and Alistair McEwan

6.1 Introduction

Immersion and diving induces a number of physiological alterations in the human body to adjust and ensure survival in changed prevailing physical conditions of the underwater environment. These adjustments can range from minor physiological system impairments to long-term health consequences or even immediate death. In order to become aware and potentially prevent such undesired outcome, biomedical monitoring can be applied to allow early warnings. However, any technology applied in underwater scenarios requires a specific design to ensure operability in this unique environment.

The two main acquisition technologies for physiological information are imaging and sensing technologies. While imaging approaches employ techniques to visualize the internal structures of an organism, sensing technologies measure external stimuli and transform them into electrical information and subsequently digital data.

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Since this book is considering those monitoring technologies that provide reliable functionality during extreme environmental exposure, imaging technologies are less suitable. Current imaging technologies require high processing power and substantial power supply, resulting in large sized devices, which present a significant obstruction for someone exposed to extreme environments. Although hand-held imaging devices may be available, these technologies mostly require a non-moving subject to obtain accurate measurements. During extreme environmental exposure, such a scenario seems unlikely. Adversities associated originating in extreme environments, such as high pressure forces and unpredictable motion, discourage the use of imaging technology during biomedical monitoring. Hence, these technologies will not be of a primary focus but may be referred to as an alternative investigation tool for post-exposure assessment.

Sensing and monitoring technologies comprise several modalities to measure environmental and biomedical stimuli. These can be divided into bio-electric, electro-chemical, bio-mechanical, optical, and acoustic sensing technologies. Some of these can be applied in underwater scenarios [1] and will be investigated in more detail in the following, including challenges to overcome, proposed solutions, and application examples.

However, some sensing modalities rely on invasive measurements. This comprises any sensing modality that requires a penetration of the skin and invasive access to obtain data acquisitions, e.g. invasive blood pressure or blood gas saturation measurements. As these approaches can pose a significant health risk, especially during extreme environmental exposure, they are not further considered in this chapter.

6.2 Electrophysiological Monitoring Underwater

6.2.1 Challenges

Monitoring devices are designed to operate best in atmospheric conditions, which is in the rather poorly conductive atmospheric air. Any electrophysiological signal acquisition device is intended to operate on high impedance inputs from bioelectrical sources [2]. The subject's skin surface and the device's measurement electrode from an electrode–skin interface create a high input impedance $Z_{IF}(= 10\,\mathrm{k}\Omega)$.

However, water, when compared to atmospheric air, has different electrical properties, primarily the high electric conductivity. Water can therefore be represented as a low ohmic impedance $Z_{water}(= 10\,\Omega)$.[1]

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[1] The resistivity of water highly depends on the number of conductive ions inside the liquid. Seawater has a resistivity of $Z_{sw} = 0.2\,\Omega/\mathrm{m}$. Drinking water's resistivity ranges from $Z_{dw} =$ 2–200 Ω/m, and deionized water has the resistivity of $Z_{iw} = 180\,\mathrm{k}\Omega/\mathrm{m}$ [3, 4].

A person immersed in water (for the purpose of this example consider a mountain lake of fresh water) is equipped with a wearable (waterproofed) ECG device with its electrodes directly attached to the person's skin. Upon underwater exposure, both the impedance value comprising the environmental water and the electrode–skin interfaces are set in a parallel circuit design.

Following the mechanism of a parallel circuit, the high impedance value of the electrode–skin interface is effectively reduced to a low ohmic value as a result of the high conductivity of water. This is in violation with the device's instrumentation amplifier's requirement for accurately measuring electropotentials.

Thus, in underwater settings measured output voltages from an instrumentation amplifier progress towards zero, making electrophysiological measurements almost impossible. In atmospheric conditions, on the other hand, the poorly conductive air does not interfere with the input impedance.

Generic solutions to overcome this issue would be to ensure a high input impedance by insulating the electrodes, or to redesign a functional sensing technology. Both approaches will be introduced in the following.

6.2.1.1 Electrophysiology Fundamentals

Under atmospheric conditions the acquisition of physiological information commonly relies on electrophyiological measurements such as the electrocardiogram (ECG) for cardiovascular, electromyography (EMG) for muscular, or electroencephalogram (EEG) for neurological diagnostics. The introduction of the concepts in the following will focus on the ECG as an example.

The human body can be interpreted as a volume conductor. This means it consists of a conductive medium based on electrolyte compositions in which bioelectrical signals can be generated and propagated. Cardiac activity in the form of muscle contraction is initiated by cardiac excitement. The flow of Na^+, Ca^+, and K^+ ions across membrane boundaries on a cellular level causes the electrocardiac potential excitement, which can be measured on the body's surface. Due to the ions' flow, a linear relationship between current I and the potential Φ can be assumed and translated to the equation:

$$I = -\sigma \nabla \Phi. \tag{6.1}$$

The conductivity tensor σ is inhomogeneous, because it differs for bone, tissues, blood, and other internal organs. Depending on the placement of the measurement electrodes, the signal form changes to varying forms of amplitude and phase of the bioelectric potential. Generically, the biological surface potential can be described using electrical field theory:

$$\Phi(\mathbf{r}) = \frac{\mu_0 c^2}{4\pi} \int \frac{\rho(\mathbf{r})}{|\mathbf{r} - \mathbf{r}'|} dV', \tag{6.2}$$

where Φ is the potential at the location **r** with ρ the conductivity of the medium and the two constants of speed of light, c, and the relative permittivity, μ_0, of the medium [14, 15].

These bioelectrical potentials are obtained using specific electrical amplifiers. The electrodes are the first instance of the bioelectrical signal acquisition and thereby operate on the high input impedances generated by the electrode skin interface.

6.2.1.2 Potential Measurement

Bioelectrical signals are derived using potential measurements following the concept of voltage adjustment. This means that a voltage source's impedance (the human body) has to be multiple times smaller than the input impedance of the measurement circuit. The high input impedance of the measurement amplifier facilitates acquisition of potential difference ($V = \Phi_1 - \Phi_2$) between two measurement electrodes (Fig. 6.1).

An obtained bioelectrical signal can be divided into two proportions, an information signal and an overlapping noise signal. In general, the noise signal is distributed equally in phase and amplitude throughout the entire body constituting a common mode signal. Thus, noise signals can be technically removed by the design of a

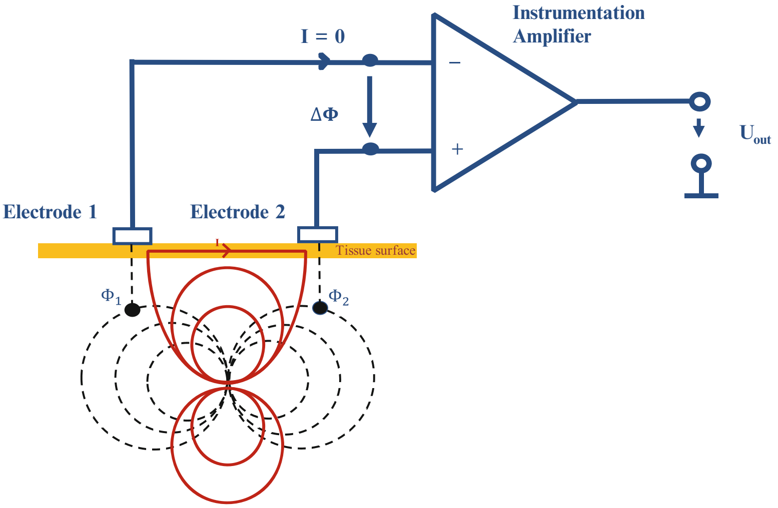

Fig. 6.1 The bioelectrical source is represented as black dashed equipotential lines. Along with the emerging equipotential lines are the current lines (red lines) in the electrical field. Potential-based acquisition technology (instrumentation amplifier) measures two potentials (Φ_1 and Φ_2) at different positions in the dipole field. U_{out} is the amplified signal from the measured potential difference $\Delta\Phi = \Phi_1 - \Phi_2$

circuit including differential gain and a common-mode rejection, which are the fundamental components of an instrumentation amplifier.

6.2.2 Current Measurement Technology

One solution to the underwater monitoring challenge is to design a new functional technology that compensates for the loss in input impedance. A promising approach was first introduced by vonTscharner [5–7] in his approach to obtain a greater resolution of EMG measurements and the subsequent application in submersed conditions. The EMG technology was further adapted for ECG purposes by Gradl et al. [13] and will be briefly discussed as a technological solution to enable underwater monitoring.

The method for current-based ECG only differs slightly from the common potential ECG. The current ECG no longer measures the potential differences but rather captures currents that arise from the cardiac excitation cycles. These currents occur as a result of Na^+/K^+ ion streams through membrane channels for the activation of cardiac excitement. It is thereby assumed that these currents, similar to the potential fields, unfold and propagate all the way to the body surface [5, 6].

In order to measure these currents, an amplifier circuit with a low input impedance is required to facilitate the current flow into the amplifier. By definition, this would be similar to the situation occurring during the potential measurements in immersed conditions. Such a circuit can be realized employing a trans-impedance amplifier (TIA) as the central element in the front-end stage of the sensing circuit [7, 13]. TIAs convert a current I_{bio}, originating from the bioelectric source, into a proportional voltage output U_{out} according to Ohm's law.

$$U_{out} = I_{bio} \cdot R_{TIA}. \tag{6.3}$$

As previously mentioned, the key difference to the potential-based bioelectrical signal acquisition is the input impedance.

While potential-based amplifiers require high input impedances, the TIA operates on low ohmic input. The low ohmic input is realized using a virtual short cut at the input stage of the amplifier (Fig. 6.2). Thereby, the amplifier's non-inverting input is connected to a reference electrode, which is set to a reference potential Φ_0. This effect is called active grounding caused by the amplifier's feedback loop to the inverting input, which also serves as the measurement input.

Current-based measurement methods were successfully utilized to monitor EMG and ECG signals in underwater conditions [7, 13].

Operational functionality for the transimpedance amplifier requires a low ohmic input stage. Due to this property, the resistivity of water has no significant impact on the measurement modality (Fig. 6.3).

Under atmospheric conditions, both modalities record ECG signals. The ECG signal of the potential modality is hardly recognizable during immersion and

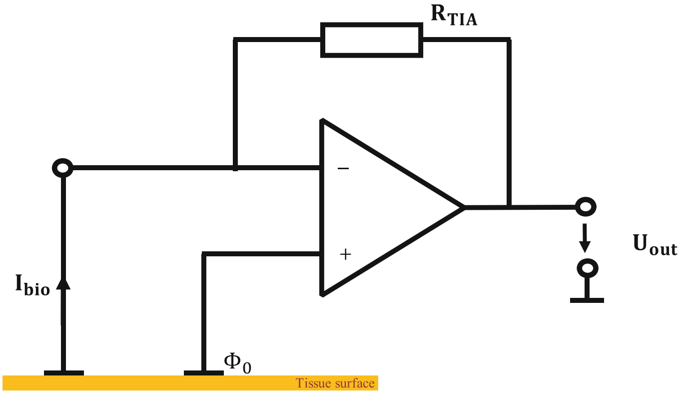

Fig. 6.2 The transimpedance amplifier (TIA) constitutes the fundamental circuit element to measure biologically emerging currents on the body surface. TIA translates the acquired currents into potential signals that can process similar to common voltage signals

severely distorted due to the loss in signal strength. However, the current modality is more stable with recognizable amplitudes of cardiac events.

6.2.2.1 Insulation and Electrode Design

A different approach to realize underwater physiological data acquisition is by ensuring that a high input impedance is provided through keeping water away from the electrode skin interface. Figuratively speaking, in this approach the low ohmic impedance Z_{water} is removed from the circuit (see Fig. 6.3).

In scientific underwater settings, a regularly applied practice is to insulate and seal standard Ag/AgCl (sliver/silver-chloride) electrodes using adhesive, hydrophobic material. Preferred adhesive materials are usually silicon based, and often a combination of multiple hydrophobic materials. As an example in the study by Sieber et al. [8], a silicon-rubber based, two-component material was used to cover and seal the electrodes. In addition, they added water-resistant tape to improve waterproofness and fixture of the electrodes.

However, these approaches come at a cost of comfort and long-term applicability. Adhesive and insulation material can lead to discomfort, movement restrictions, and skin irritations, especially when applied over an extended period of time. Studies have also shown that there is a chance that the adhesive material becomes weak and loses its water resistance causing water to leak into the electrode–skin interface [9]. Furthermore, the adhesive material may become elastic causing the electrode to move across the skin surface, resulting in a degradation of the signal's quality [12].

Rather than using extensive insulation material, specialized electrode design could be employed in submersed conditions. There are several approaches in designing water-resistant electrodes [10–12]. These electrodes were combined with

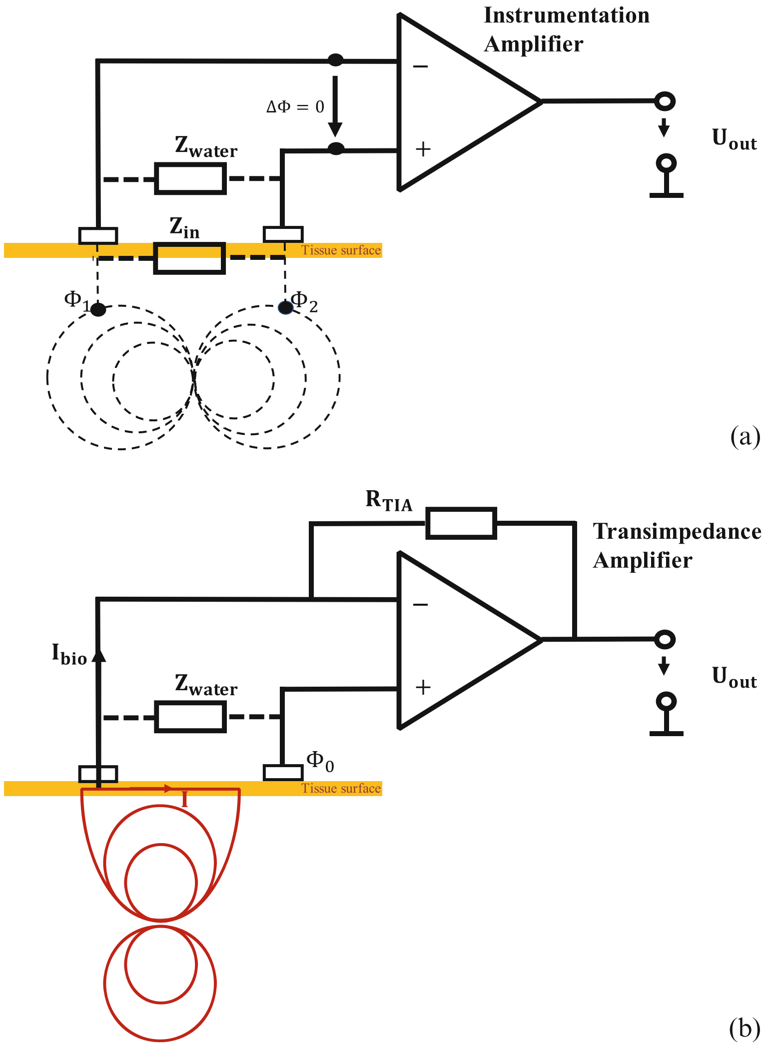

Fig. 6.3 The two measurement modalities: (**a**) potential-based employing an instrumentation amplifier and (**b**) current-based employing a transimpedance amplifier, depicted while operating in underwater condition. Immersion is represented as a low ohmic impedance Z_{water} set in parallel to the electrode skin surface [13]

a sensing component and with water-repellent material. Different hydrophobic components are mixed together and/or are arranged in a multilayer layout. The water repelling materials prohibit water to enter the electrode area, which is dedicated for the sensing operation. A list of current electrode design approaches is provided in Table 6.1.

Table 6.1 Different approaches of electrode designs for application in underwater conditions. The designs comprise different materials, concepts, and initial performance testing in laboratory settings

	Materials	Concept	Performance
Othsu et al. [9]	Electrodes are coated with a five-layer design covered with antistatic silicone	Waterproofed electrode with a high-input impedance amplifier; water-resistant material served as electrode–skin interface, including a driven-shield technique	No significant signal attenuation observed between dry and immersed conditions
Reyes et al. [10, 11]	Polydimethylsiloxane (PDMS) and carbon black (CB)	Conductive material uniformly distributed inside the PDMS polymer matrix facilitating electron transport	Tested in dry, wet, and full immersion conditions. Signal quality correlated in dry and wet conditions. During full immersion, signal degeneration [12]

To date all of these electrodes are proof-of-concept studies with limited tests in actual real-world scenarios. Most studies only comprise laboratory settings and it remains to be seen if they are applicable for actual diving scenarios.

6.3 Data Science for Biomedical Monitoring

Biomedical monitoring also requires an information science component responsible to process and visualize recorded data provided by the sensors. For effective data handling, it is common practice to assess data through multiple steps. These include data collection, acquisition, transmission, analytics, and visualization. By following these steps, it can be ensured that any obtained data is processed efficiently to create reliable and accurate data visualization.

Data Collection

The collection of data refers to any technology with the capability to sense and collect data. These sensing technologies and their functionality are comprehensively described for the underwater use-case in the previous sections.

The usual practice for continuous data collection in underwater scenarios is that the data collected is stored on a local memory on the wearable device. Electromagnetic data communication, such as Bluetooth, or WiFi, are extremely weak in underwater conditions and only provide a stable connection in the range of one centimetre. Other communication methods, such as ultrasound or optical solutions, tend to be unpractical for implementation in wearable devices.

Data Acquisition and Transmission

Given the limitations posed by the environment, in underwater conditions data is usually acquired on an onboard memory of the sensor device for retrospective analysis. After exposure, the data is transferred to a computer where all analytical and statistical evaluations are performed.

Although the limitations for data transmission are direct, there have been some approaches to enable real-time data transmission between the sensor device and an end-device, which provided to opportunity for observation [1, 16]. Such instalments, however, are mechanically weak and tend to fail in roughening environments. Any wired connection can be a life-threatening hazard for a subject underwater and thereby limit the degree of movement freedom for the subject.

Short-range wireless communication underwater has been introduced and is under development [16]. Although these approaches would enable short-range communication, which would provide the opportunity for multi-sensor embedded monitoring, the limitation of short-range transmission remains. Observers who evaluate the data are not usually considered to participate in the diving activity and to be in approximate range to the diver. Thus, wide-range communication through different media, e.g. air and water, are still on high demand for underwater applications [1, 16–18].

Data Analytics

At the current stage, data analytics for data obtained in underwater conditions is limited to retrospective analysis or laboratory settings. In the scope of data analysis in underwater settings, analytical efforts are centred around the evaluation of continuous data streams from subject data and correlated with environmental data. For example, a diver's heart rate is correlated to the diving depth and corresponding ambient pressure effects. The continuous data sets are commonly analysed for feature and event detection and extraction using a variety of different time-domain and frequency-domain analytic tools. In addition, a large scope of statistical evaluation is employed to provide statements about absolute and relative changes in data sets [22].

To date, the most common and arguably most valid analysis tool for biomedical monitoring and assessment in diving is the heart rate variability analysis. The interested reader is hereby referred to the following literature [19–24].

6.4 Pre- and Post-Assessment Technology

Commonly, an underwater exposure period is accompanied by pre- and post-exposure settings. These two settings may provide the opportunity to obtain extensive data collection, which cannot be obtained while being exposed. Pre- and post-assessment technology comprises any technology that cannot be worn during underwater exposure or requires invasive application for data collection.

The collection of blood samples poses an important technique to assess adaptational mechanisms in genetic, hormonal, or inflammatory markers. Evaluation of blood samples requires extensive laboratory technology and time. A detailed listing of different technologies and bio-chemical evaluation concepts would be beyond the scope of this chapter and therefore the interested reader is encouraged to seek further information from the following sources [25–28].

In scuba diving it is common to apply echocardiography or ultrasound measurements to monitor physiological changes. Both technologies provide imaging technologies to evaluate any kind of adaptational change as a result of submersion. A special feature is the effect of decompression illness and the formation of venous gas bubbles. The number of occurring bubbles may indicate the susceptibility to diving stress. To data the only reliable tool to determine the existence of gas bubbles is using ultrasound technology.

Although not providing a continuous data set, pre- and post-assessment technology provides additional approaches for fundamental research into diving physiology. Given that certain physiological adjustments are only assessable through pre- and post-assessment technology, these approaches are a useful and necessary addition to wearable technologies.

6.5 Discussion

Electrophysiological monitoring underwater is naturally constrained by the prevailing environmental conditions. Physiological data monitoring in the world undersea requires a specialized technology design to withstand the unique conditions present in this extreme environment. Especially the high electrical conductivity property of water poses a significant challenge that needs to be addressed to achieve electrophysiological monitoring. Several technological approaches for underwater electrophysiological data collection have been presented in this chapter, ranging from simple insulation and waterproofing of measurement electrodes to a modern design of electric circuit sensing technology. These approaches showed promising performances in proof-of-concept studies, enabling new research opportunities to study physiological changes in underwater environments.

However, the conditions of the underwater environment not only have an impact on the design of sensing modalities but also impose strict limitations on subsequent data science approaches. Data transfer and inter-device communication options are limited undersea. Current data transfers rely on Bluetooth or WiFi connections, which are electromagnetic data communication approaches. Thus, data transmission from sensing devices attached to a diver underwater to a data observer, who is commonly located outside of the underwater environment is only achievable with great logistical efforts. To date, the practice of underwater physiological data collection is based on data storage on the sensing device and the data analytics occurs in post-exposure settings.

Thus, generally speaking, there is no way around wearable technologies if continuous data is required for biomedical monitoring in underwater conditions. Modern advances in wearable technology enable the collection of various physiological parameters, such as heart rate, blood pressure, impedance cardiography, oxygen saturation, body segment inertia and orientation, and body temperature [24, 29–31]. A comprehensive review of wearable technology for safety and performance in divers was performed by Vinetti et al. [30]. To date, the technology is lacking large-scale testing and application multi-sensor platforms. Larger-scale testing protocols would enable the wearable technology to be listed as consumer technology, or even medical graded technology, thereby providing further confidence for their applicability. The combination of several sensor modalities into a multi-sensor platform could enable the assessment of multiple data streams, thus, multiple biomedical information, simultaneously and provide the opportunity for easy comparison of the data streams.

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Part III
Space

Chapter 7
Space as an Extreme Environment—Galactic Adventures: Exploring the Limits of Human Mind and Body, One Planet at a Time

Anastasiia Prysyazhnyuk and Carolyn McGregor AM

7.1 Introduction: Background and Driving Forces

Space has always sounded futuristic, but over half a century of scientific exploration and research has made it nearly second nature for human kind. It brought realization that "the Earth is a very small stage in a vast cosmic arena" (Carl Sagan), presenting endless opportunities for discovery of other habitats within the solar system.

Literature on space exploration history is sparse, as it originated as a branch of military flight and national defense services during the post-war period [19, 23] and slowly evolved into a separate field of science, the major contributors of which were the former Soviet Union and the USA.

Early manned spaceflights date back to the 1960s, when very little was known about how the human body would respond to conditions of spaceflight [19]. The Soviet Union, as the pioneer of human spaceflight, performed terrestrial simulation experiments and animal spaceflights in the late 50s, to understand physiological deviations that occur under conditions of spaceflight [19]. The acquired knowledge informed and prepared the first man, Yuri Gagarin, to be successfully launched into outer space on April 12, 1961, which marked the beginning of the era of human space exploration. Since then, there were many failures and successes in the history of manned spaceflights, a snapshot of which is summarized in

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Fig. 7.1. The figure displays a significant number of breakthroughs for humankind, which were achieved within a decade of the first manned spaceflight, including the first man and woman astronaut in space, first extravehicular activity, in-orbit crew transfer, first manned landing on the Moon, and launch of the first space station, Salyut 1. As becomes evident from Fig. 7.1, the former Soviet Union and the USA embarked on a space race, following the first human spaceflight, in an attempt to put the first man on the Moon. Subsequently, numerous space shuttles and space stations have been launched by both nations, until the assembly and launch of the International Space Station on November 20, 1998, which has been permanently occupied ever since. Another important milestone in Fig.1 denotes evolution of space exploration as a niche of commercial activity, representing the first recreational space flight completed on April 28, 2001, when the first space tourist travelled to the International Space Station.

As space missions continue to increase in complexity of mission objectives, duration and distance travelled, the health and well-being of astronauts remains the top priority for space agencies and government officials, necessitating comprehensive health monitoring and development of clinical decision support systems to preserve an optimal performance and well-being of the crew. As such, it is important to delineate implications of space travel on the human body.

7.2 Space as an Extreme Environment

Space or rather the Lower Earth Orbit (LEO) has been the main designation for human space exploration to-date. It is a unique habitat, some aspects of which can be studied in ground-based analogs and laboratories. The hazards of spaceflight environments can be classified into five broad categories, including radiation, isolation and confinement, distance from Earth, gravity (or lack thereof), and lastly, hostile closed-loop spacecraft environment [31].

Gravity
Earth's gravitational force is fundamental for optimal performance of human body systems. Human space exploration has shown that our bodies are capable of adapting and functioning under conditions of weightlessness, while there are numerous deleterious effects associated with that environment, some of which can be counteracted or reduced through countermeasure regimes.

Radiation
Space radiation is one of the main hazards that astronauts are exposed to. Astronauts are exposed to significantly higher levels of radiation than the general population on Earth, placing them at a greater risk of developing various radiation-induced pathological states and contributing to increased morbidity and mortality rates. Mitigation of this effect necessitates development of strong and reliable radiation shields, especially as human space exploration extends to deep space, outside the Earth's protective magnetic field.

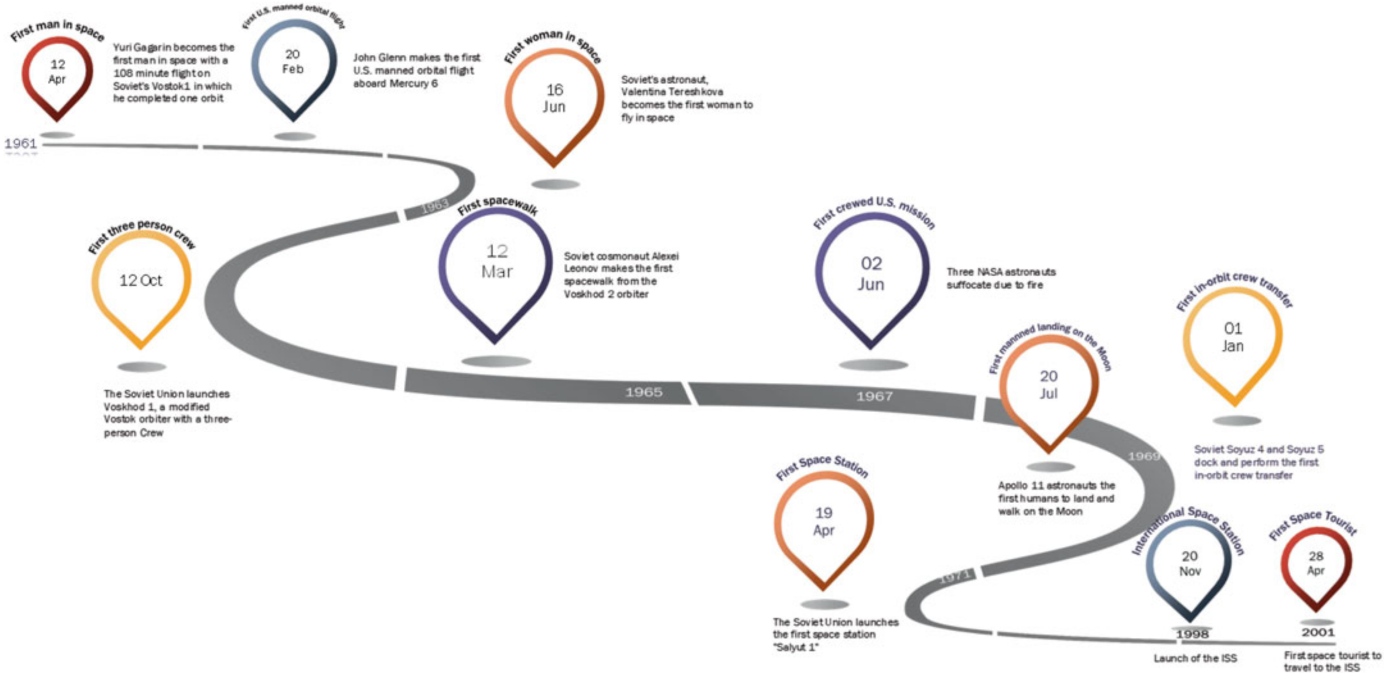

Fig. 7.1 Milestones of manned spaceflight history

Distance from Earth
The distance from Earth is also an important hazard both physically and psychologically. There is a sense of comfort that astronauts have looking out of the International Space Station cupola and seeing Earth in relative proximity. This can have important psychological implications during missions to the Moon and Mars, when the distance to Earth significantly increases. In addition, the distance from Earth has important logistical implications, including communication delays, inability to return should an emergency arise and relatively limited medical and technical expertise aboard the spacecraft.

Isolation and Confinement
Isolation and confinement can be defined as psychological stressors that test human behavioral flexibility and adaptability. Despite stringent selection processes and training protocols, behavioral issues among the space crew become inevitable, as a small group of people is confined within a small space for prolonged periods of time. As such, it has implications on team dynamics, physical health, and performance.

Closed-Loop Spacecraft
A closed-loop spacecraft system is an important environmental system that ensures habitability, safety, and comfort of the crew during space exploration. A closed-loop environmental system implies that the functionality of the system is based on the feedback received from the system's output components, which in turn have the ability to control and vary the magnitude of the input signal. Some of the components of the closed-loop environmental system include temperature, pressure, relative humidity, light levels, and water quality. The risks associated with a closed-loop system include cabin toxicology and microbial contaminations, which have direct health implications for the crew.

Implications of Prolonged Exposure and Deep Space Exploration
Each of the hazards has a profound effect on human mental and physical health, as well as occupational performance. The effects of prolonged exposure are more severe, especially as humans embark on deep space exploration, outside the Earth's protective magnetic field. An in-depth review of psychological and physiological effects associated with space travel will be provided in sections to follow.

7.3 Impact of Space Exposure on the Human Body

Astronauts are a high-risk population exposed to an array of unique extreme environmental conditions that trigger various psychological and physiological responses, challenging adaptation capacity of the human body [9, 15]. Space exploration has necessitated that humans and animals be exposed to weightlessness or microgravity environments where the effects of gravity are not felt. They are exposed to greater levels of radiation and are at risk of exposure to solar flares and toxins within the spacecraft and spacesuits.

Environmental conditions of the spacecraft may be dangerous and even life threatening if the necessary control measures are not taken to monitor, minimize, and protect crew members from the impacts of microgravity or weightlessness together with exposure to radiation, solar flares, and cabin environment toxicology [9, 15].

In addition to the physical impacts of space travel, the missions impact astronauts psychologically due to isolation, confinement, and the stress of astronaut tasks within space flights. These psychological, physiological, and environmental issues of spaceflight become significantly important as space explorations expand to habitats of increased travel distance and mission duration. These longer missions are also necessitating development and implementation of appropriate increased radiation shields and waste management systems [9].

Half a century of space research and exploration have demonstrated human capacity to survive and effectively function in orbital and sub-orbital habitats [9]. Implications of human space travel have been thoroughly investigated through missions of variable distances and duration, as well as in Earth-based simulation environments through post mission analysis. Experimental findings have formed the foundation of space medicine and onboard medical capacity, including development of countermeasure systems, in order to minimize and eliminate deleterious effects of weightlessness, improve adaptation capacity, and ease the recovery processes upon return to Earth [1, 9]. It is important to employ an integrative approach when considering psychological, physiological, and environmental aspects of spaceflight environment, as summarized in Fig. 7.2. In addition, development of closed-loop life support systems should be considered for crew's health and safety, should the delivery of life sustaining supplies be limited or impossible [9].

7.3.1 Physiological Implications

The human body is exposed to an array of physiological effects associated with microgravity and other conditions of spaceflight. Onset, duration, and severity of physiological changes are subject to individual differences and duration of the mission. Figure 7.2 summarizes physiological effects by body system that have been reported during both short- and long-duration missions, the latter being identified as any mission that lasted over a month [18].

7.3.1.1 Musculoskeletal System

The musculoskeletal system is directly affected by conditions of spaceflight due to the lack of gravitational loading and orthostatic intolerance. As the gravitational loading is reduced, bone and muscle activity declines, thereby contributing to muscle weakness, reduction in motor function, and metabolic demands [12, 15, 16]. Fluid re-distribution and activation of compensatory mechanisms induce loss of

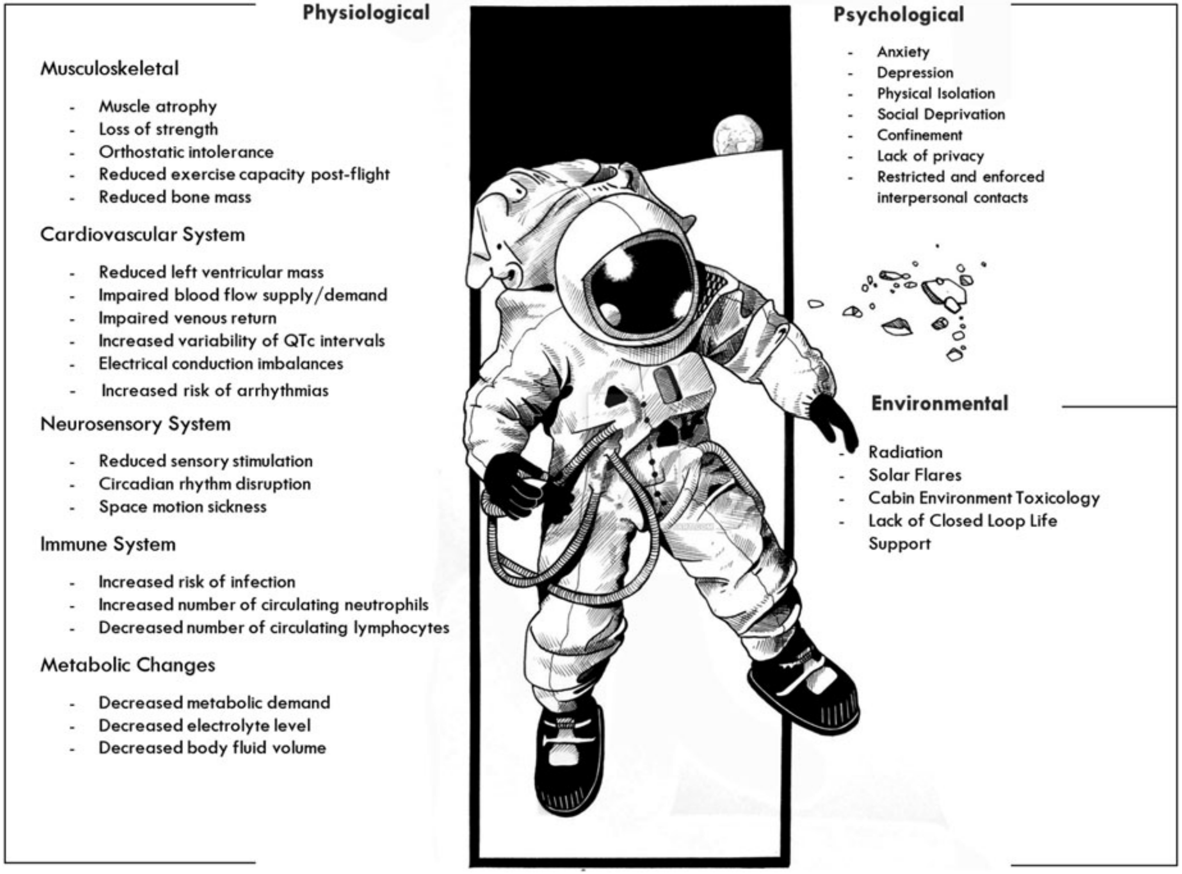

Fig. 7.2 Impact of spaceflight conditions on the human body

minerals, such as phosphorus and calcium, which contribute to reduction of bone mass and decrease of muscle strength, eventually resulting in muscle atrophy [9, 11, 15]. Loss of muscle strength not only impedes endurance but also increases the risk of fracture during spaceflight and upon return to Earth. Previous studies reported that astronauts suffer from increased bone fragility and decreased exercise capacity post-flight [15]. Also, increased bone resorption and decrease of fluid volume during spaceflight may increase the risk of kidney stone formation. However, it should be noted that severity of clinically presented symptoms varies depending on the application of countermeasures and duration of the mission. A variety of countermeasure systems and exercise regimes have been implemented into the daily activities of astronauts to reduce muscle atrophy and increase astronauts' fitness during the flight, while minimizing post-flight re-adaptation discomfort [9, 15].

7.3.1.2 Cardiovascular System

The environment of microgravity induces a combination of rapid physiological changes that contribute to cardiovascular deconditioning, as shown in Fig. 7.2. Cardiovascular deconditioning can be described in terms of numerous clinical symptoms subject to individual differences, duration of the mission, and use of countermeasures during spaceflight or in terrestrial simulation environments [8, 9, 15, 22]. It should be noted that cardiovascular deconditioning is attributed to fluid shift, also known as intravascular hypovolemia, rather than inactivity. The mechanisms and triggers of cardiovascular deconditioning remain poorly understood despite decades of space cardiology research [8].

As the spacecraft launches and reaches orbit, astronauts experience a rapid fluid re-distribution in the cranial direction, accompanied by swelling of the head, neck, and thorax [9, 15, 16]. Increased cardiopulmonary volume induces increase in central venous pressure and subsequent venous return [14]. The cardiovascular system perceives the fluid shift as an increase in total circulating blood volume, thereby activating regulatory mechanisms that induce reduction of blood plasma volume and decrease in red blood cells mass [9]. Regulatory mechanisms activate in order to compensate for perceived increase in volume and build-up of pressure in the upper regions of the body. Subsequently, the heart rate and stroke volume elevate to maintain appropriate cardiac output, despite impaired blood flow supply and demand [4, 12]. Also, previous studies reported impaired baroreceptor reflex function, clinically presented as reduction of sensitivity by approximately 50% during the first hours of weightlessness, yet the sensitivity was restored to adequate levels by the third hour [4, 12, 14].

The aforementioned cardiovascular changes not only lead to suppression of electrical and mechanical activities of the heart but also contribute to decreased orthostatic tolerance and increased susceptibility to arrhythmias [9]. As the regulatory mechanisms enable the human body to adapt to conditions of weightlessness the mean heart rate and blood pressure reduce to nearly pre-flight values, indicating a possible reduction of sympathetic activity, enabling the astronaut to establish an adequate level of performance during the mission [3, 8]. Nevertheless, mean arterial pressure and heart rate increase above the pre-flight values upon return, as astronauts begin to re-adapt to Earth's gravitational forces [2, 16].

Long-term space flights have been associated with cardiovascular changes of higher magnitude and intensity that required a much longer post-flight recovery. Long-term space missions are associated with prolonged cardiac conduction and repolarization, while measurable reduction in left ventricular mass is observed [6, 7, 18]. Nevertheless, it is speculated that the process of left ventricular mass reduction is attributed to dehydration, rather than cardiac muscle atrophy [13, 22], while hydration during extravehicular activities may reduce electrolyte imbalance and proneness of dysrhythmias [20].

7.3.1.3 Neurosensory Disturbances

Elimination of head-to-foot gravitation force induces an array of physiological effects accompanied by space motion sickness and other neurosensory disturbances, together with re-distribution of bodily fluids and marked swelling of the upper body structures [5, 8, 14, 15, 22].

Space motion sickness is clinically presented as headache, dizziness, vomiting, fatigue, and orthostatic intolerance [10, 14]. However, it is a relatively short-term effect that diminishes several days into spaceflight. Other neurosensory disturbances, such as disorientation, tend to have a long-term effect. Disorientation results from reduced sensory stimulation, such as absence of familiar spatial cues and awareness of self within a particular environment. Adaptation of vestibulo-ocular reflex may take several months, while astronauts may experience illusions that may recur occasionally during long-term space flights. In addition, reduction of sensory stimulation not only leads to disorientation but also disruption of circadian rhythms, which may affect astronauts' productivity and sleep–wake cycles [15, 16].

7.3.1.4 Immune System

Astronauts do not seem to suffer from reduced immune system function nor have the findings of altered immune system been consistent [10]. However, changes in immune system function may be of higher significance as mission duration increases and spacecraft becomes more susceptible to impairment of environmental control systems and increased cabin toxicology [9, 15]. The possibility of increased microbial population on the spacecraft may lead to reduced immuno-competence of crew members, characterized by increased number of circulating neutrophils, reduced number of circulating lymphocytes and eosinophils, as well as an overall increase in susceptibility to acquire an infection or disease [9]. However, further investigations are required to support these findings.

7.3.1.5 Metabolic Changes

Re-distribution of bodily fluids triggers a cascade of metabolic changes, since it is perceived as an increase in total circulating blood volume. This leads to activation of compensatory mechanisms and reduction of plasma and extracellular fluid volume, the onset of which alters electrolyte balance and contributes to loss of vitamins and minerals [14, 15]. Altered electrolyte balance does not seem to manifest in clinical symptomology, yet interferes with the function of other bodily systems.

7.3.2 Psychological Implications

As noted in Fig. 7.2, there are considerable psychological aspects of spaceflight. Despite stringent selection and training protocols astronauts may suffer from psychological distress due to isolation and confinement within space module, restricted mobility, enforced interpersonal contacts, lack of familiar surroundings, and reduced interaction with family and friends. Diminished personal "ownership" and lack of privacy contribute to noisy environment and sleep disturbances, which result in decreased physical and mental performance, contributing to the development of interpersonal conflicts [17, 21]. In addition, astronauts may suffer from anxiety, depression, social withdrawal, and impulsive behavior. Finally, many tasks that astronauts need to perform during missions are stressful and many situations can arise that require immediate critical decision making. The severity of psychological conditions is closely associated with the duration of the mission, which not only affects the harmony of the crew but even more so threatens execution of mission objectives and safety of the spacecraft [21]. As such, comprehensive psychological countermeasures have been incorporated into daily activities of astronauts, to provide stimulating and meaningful activities that foster a positive environment and enhance well-being, cohesiveness, communication, and harmony of the crew. In addition, astronauts are taught a variety of coping strategies to develop adaptive behaviors, minimize and resolve interpersonal conflicts, improve self-reflection and acceptance of cultural heterogeneity, which contribute to improved performance of the crew [17, 21].

7.3.3 Impact of Biological Sex and Gender on Health and Wellness in Space

To date the impact of biological sex, defined on the basis of individual's genetics, and gender, based on individual self-representation in a social setting, on health and wellness in space has been understudied [24]. The aforementioned physiological effects were reported predominantly for male astronauts, and differences for the female population are not well known. However, males continue to dominate the field of space research and data on female effects associated with conditions of weightlessness remain a limiting factor in the current body of literature.

According to the international astronaut population demographics, published in June 2013, a total of 534 humans have travelled to space, of which only 57 were women [24, 25]. There have also been significant differences in social determinants, such as the marital status, education level, and field-expertise reported for each biological sex, which may have contributed to the differences in adaptation to conditions of spaceflight. Goel et al. report that the US male astronauts have significantly higher military experience (72.8%), in comparison to the female astronaut population, who had a significantly stronger educational background, with nearly twice the percentage of doctoral degrees (50% vs 28% for male population) [24, 25].

Over the last decade, numerous initiatives, including national workgroups and Earth-based simulation studies have been launched to investigate biological sex differences in human adaptation to extreme environments.

A National Concilium was arranged in the USA to investigate how sex- and gender-based differences impact the effects of spaceflight on specific body systems, such as cardiovascular, neurosensory, immunological, musculoskeletal, and reproductive systems [26]. In addition, psychological effects and behavioral changes were also assessed [24, 25]. The national workgroup conducted a thorough review of all published literature on sex- and gender-based differences associated with adaptation to spaceflight conditions. A snapshot of main differences that have been observed is summarized in Fig. 7.3.

7.3.3.1 Physiological Differences

Anatomical differences in biological sexes have a profound effect on body's ability to adapt to extreme environmental conditions, such as those encountered during space travel. Space flight conditions can activate a cascade of physiological reactions that can ultimately lead to differential outcomes in female and male astronaut populations. As such, physiological differences on the basis of biological sex are reviewed according to the body systems they effect.

Male astronauts are known to have a greater bone and muscle mass, which makes them less susceptible to post-flight orthostatic intolerance, following muscle and bone unloading encountered during spaceflight, as opposed to their female counterparts.

The severity of cardiovascular deconditioning is more pronounced in women rather than men, since they experience a greater loss of plasma volume, reduced leg vascular resistance, and a greater elevation of the heart rate in response to stressful stimuli. As such, women are subjected to higher incidence of cardiovascular morbidity and mortality [24].

Neurosensory disturbances observed in female and male astronaut population vary significantly, which may be attributed to anatomical differences of the brain,

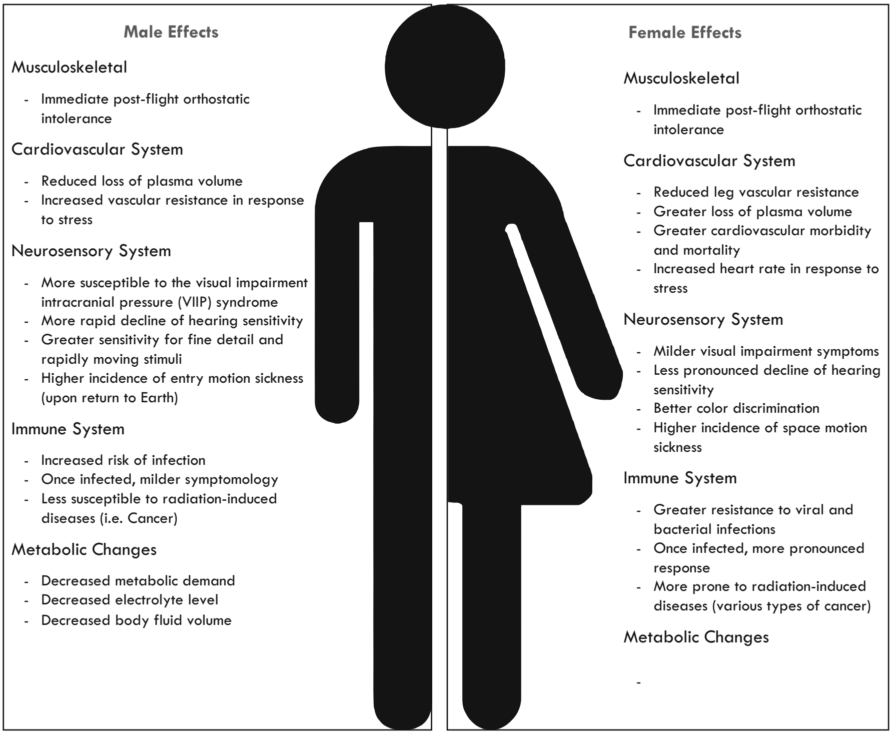

Fig. 7.3 Key differences in female vs. male adaptation to conditions of spaceflight, on the basis of biological sex, created from [24]

as well as differential activation of neurosensory pathways [26]. Men are more susceptible to development of visual impairment intracranial pressure (VIIP) syndrome, as well as suffer from more rapid decline of hearing sensitivity in-flight. In addition, men and women experience differential visual sensitivity in-flight, where men demonstrate greater sensitivity to fine detail and rapidly moving stimuli, while women have a much better color discrimination [24]. Also, women have more severe space motion sickness, while men have a greater incidence of entry motion sickness experienced upon return to Earth.

Women experience a greater resistance to viral and bacterial infections in-flight. However, once infected, their symptomology is more pronounced than in their male counterparts, making them more susceptible to development of autoimmune disorders. It should also be noted that female astronaut population is more susceptible to radiation-induced diseases, including various types of cancer, such as breast, ovarian, and lung. Due to severe radiation-induced physiological responses during spaceflight, women are allowed to spend significantly less time in space than men.

It has also been reported that both men and women astronauts are prone to temporary infertility as a result of exposure to high-dose acute ionizing radiation

[24]. However, no long-term effects have been reported in the literature nor have any longitudinal studies been performed to further investigate this issue.

It is important to note that reported findings for the female population represent a small sample size and as such cannot be conclusive of the reported differences, unless a greater sample size is analyzed.

7.3.3.2 Psychological Differences

Psychological aspects of spaceflight environment as well as group dynamics in a female population have been assessed in terrestrial simulation studies. One such study was the first all-female analogue mission "Luna 2015" simulating a mission to orbit the moon, completed in Moscow in 2015. The experiment utilized an Earth-based hyperbaric chamber located at the Institute of Biomedical Problems of the Russian Academy of Sciences (IBMP RAS) that simulated some of the spaceflight conditions, including confinement and isolation. The main study objectives where to investigate the effects of confinement and isolation within a first of its kind, all-female crew. The duration of the study was seven days, which is equivalent to the time it takes to orbit the Moon. Health assessments were performed in a scheduled and periodic manner. Holter-style monitoring devices were utilized to acquire electrocardiogram recordings for adaption assessments. Journals and questionnaires were used to assess behavioral and psychological well-being of the crew. The study revealed dynamic activity of regulatory mechanisms in response to various environmental, physical, and psychological stimuli, bearing an effect on overall well-being and performance of the crew. More detailed results on "Luna 2015" can be accessed in [28, 29].

Further studies need to be conducted in order to investigate the role of biological sex and gender differences in adaptation capacity and performance of the crew in orbital and sub-orbital habitats.

7.4 Pre-mission Monitoring and Resilience Assessment and Development

Remarkably, the field of space medicine evolved long before the first human spaceflight, originating from health monitoring of high-altitude pilots. Initial astronaut selection and health monitoring in-flight were based on the practices adapted from aviation medicine, and the first astronauts selected were military jet pilots [19].

Health monitoring of astronauts can be thought of as a multi-tier system, consisting of rigorous selection processes, pre-flight (baseline) data collection, in-flight monitoring, and post-flight medical monitoring. While review of each of the tiers in great detail is well beyond the scope of this chapter, a brief overview of each is provided below. Monitoring covers both physiological and psychological aspects.

The main emphasis will be on in-flight medical monitoring, as the onboard medical capacity remains extremely limited [19]. For this reason, a variety of Earth-based simulation studies are being conducted, employing an integrative individualized approach, to predict and evaluate the severity of physiological and psychological effects associated with conditions of spaceflight.

Successfully selected astronauts undergo rigorous pre-flight examinations to assess their psychological and physiological ability to cope with conditions of spaceflight. Future astronauts must possess the necessary qualities to withstand the harmful effects of perceived danger within this extreme environment, which first and foremost affect their performance and mental clarity.

The first astronauts selected within the Soviet space program underwent comprehensive training programs that tested the boundaries of the human body, both physiologically and psychologically. In particular, all Soviet astronauts completed skydiving training, during which the neuropsychic stability of the trainee was assessed. During skydiving training, the astronauts were monitored via telemetry and basic physiological parameters were assessed through collection of electrocardiogram (ECG), electroencephalogram (EEG), electromyograph (EMG), pulse, respiration rate, and blood pressure [30]. Electrodes were placed on the head, on a torso strap, on the forearms, palms, and ankles. Subsequently, astronauts underwent special resilience training through exposure to high temperatures, isolation, confinement, limited sensory stimulation, and high physiological load [30]. As a result, they developed resistance to the extreme conditions of spaceflight. These tests were also used as a surrogate to investigate the potential effects of spaceflight on the human body.

During experiments evaluating the impact of vibration on the human body they assessed heart rate, before the experiment then at the 5th, 30th, and 50th minute of the experiment and right after the experiment. No significant deviations in the activity of the heart were observed, signifying the astronaut's readiness for the spaceflight [30].

Moreover, pre-flight medical evaluations include a treadmill stress test, hematological analysis, pulmonary function tests, diagnostic imaging, and specialists' examinations [19].

In-depth pre-flight medical examination requirements are summarized in Table 7.1. It should be noted that astronaut refers to the US space program, while cosmonaut to the former Soviet/Russian space programs. The goal of both space programs is to ensure the successful astronauts are not only able to preserve optimal performance and well-being under extreme conditions but also able to exercise critical thinking in dangerous, life-threatening situations.

Moreover, the Soviet/Russian space program has always emphasized the importance of preventative rather than corrective medicine. As such, cosmonauts undergo more rigorous medical examinations in order to predict and estimate the risk and severity of physiological deconditioning that may occur under spaceflight conditions. The acquired physiological information is then used for personalized resilience training and to develop individualized countermeasure systems to alleviate deleterious effects of spaceflight environment.

Table 7.1 In-flight medical monitoring during long-duration flights on the Mir station, adapted from [19]

Astronaut candidates	Evaluation	Cosmonauts candidates
	Medical history	
NASA medical survey questionnaire		Includes surgical history
	Physical	
Includes rectal exam		Includes rectal exam
Pelvic exam & pap smear		Pelvic exam & uterine ultrasound
Proctosigmoidoscopy		
	Cardiopulmonary	
History and examination		History and examination
Pulmonary function tests		Pulmonary function tests
Exercise stress test		Exercise stress test
Blood pressure		Blood pressure
Resting & 24h ECG		Resting & 24h ECG
Echocardiogram		Echocardiogram
		Phono- & Mechanocardiography
		Cardiac cycle analysis
	Musculoskeletal	
Muscle mass		Anthropometry
Anthropometry		
	Radiographic	
[a] Chest films (PA & lateral)		Chest films (abdominal flat plate)
Sinus films		Cranium, spine, renal & urologic X-rays
Mammography		Abdominal & urogenital ultrasounds
Interview with radiation safety officer		Radioisotope liver test
Review medical radiation exposure history		Excretory urogram and urofluorometry
	Laboratory	
Complete blood workup (clinical biochemistry; hematology; immunology; serology; endocrinology)		Complete blood workup (clinical biochemistry; hematology; immunology; serology; endocrinology)
Urinalyses, including 24h urine chemistry; renal stone profile; urine endocrinology		Urinalyses, including 24h urine chemistry and renal stone profile
Stool analysis for occult blood, ova, parasites		Stool analysis for ova, and parasites
		Analysis of duodenal and intestinal secretions

(continued)

Table 7.1 (continued)

Astronaut candidates	Evaluation	Cosmonauts candidates
	Otorhinolaryngological (ENT)	
History and examination		History and examination
Audiometry		Sinus X-ray
Tympanometry		Tympanometry
		Exo- & Endoscopy
		Vestibular function
		Optokinetic stimulation
	Ophthalmologic	
Visual acuity, refraction & accommodation		Visual acuity, refraction & accommodation
Color & depth perception		Color & depth perception
Phorias		Night vision
Tonometry		Tonometry
Perimetry		Extraocular muscles
Funduscopic examination with retinal photographs		Slit-lamp examination and ophthalmoscopy
	Dental	
“Panorex” & full dental X-ray within prior two years		Orthopantomography
		Electroodontodiagnosis
		Vacuum test
	Neurological	
History and examination		History and examination
EEG at rest, with photic stimulation		Doppler study of cranial vessels
EEG during hyperventilation, Valsalva maneuver, sleep		EEG with photic stimulation
		Autonomic reflexes
		Skin thermometry
	Psychiatric and Psychological	
Psychiatric interview		Psychiatric interview
Psychological tests		Psychometric testing
		Personality inventory
		Sleep monitoring

(continued)

Table 7.1 (continued)

Astronaut candidates	Evaluation	Cosmonauts candidates
	Other/functional tests	
Drug screen		Decompression and hypoxia
PPD skin test		Centrifugation (G_z and G_x)
Microbiological, fungal & viral tests		Postural tests
Pregnancy tests		Lower body negative pressure
Screen for sexually transmitted disease		Ergometry
Abdominal ultrasound		Thermal testing
		Parabolic flight

[a] A pregnancy test is given to all-female applicants before radiographic testing

Table 7.1 summarizes a listing of medical examinations that are performed in order to assess physical and psychological fitness of selected astronaut/cosmonaut candidates. It includes a thorough review of medical history, physical examination, cardiopulmonary evaluation, and musculoskeletal examination. A variety of diagnostic imaging tests are performed, including X-rays and ultrasonography. Laboratory tests include complete blood workup, urinalyses, stool analysis and in the Russian program, additional duodenum and intestinal secretions analysis are performed. Other medical examinations include specialist's examinations, including otorhinolaryngological (ENT), ophthalmological, dental, and neurological examinations. Psychological and psychiatric examinations are conducted on the basis of tests and interviews, while sleep monitoring is also used as part of the Russian space program assessment.

The US and Russian space program medical assessments share a number of commonalities, yet some differences do exist. In particular, the Russian space program also conducts numerous functional tests, including investigations under conditions of hypoxia and decompression, centrifugation, postural tests, lower body negative pressure, ergometry, thermal testing, and parabolic flights. On the contrary, the US space program conducts drug screening, skin tests, pregnancy tests, and screens for microbial, fungal, viral, and sexually transmitted diseases. Other differences within each type of medical examinations are summarized in Table 7.1.

7.5 Health Monitoring in Space

Medical monitoring in space is defined as the "periodic physiological, clinical, and environmental evaluations to ensure that no unfavorable trends in the health status and medical risk of the astronauts have occurred, and that appropriate preventative, diagnostic, and therapeutic measures are instituted promptly so as to maintain the health, performance, and well-being of space crews" [19]. In-flight medical monitoring greatly differs from pre- and post- flight examinations, as the onboard medical capacity is extremely limited due to physical constrains and specifics of the spaceflight environment.

Table 7.2 summarizes a listing of physiological parameters and frequency of their acquisition in-flight. In addition, it includes a listing of medical monitoring modalities that are available within the spacecraft or at the space station. It should be noted that in-flight medical monitoring modalities are selected on the basis of the duration and objectives of the mission, which might require monitoring of different physiological parameters [19]. In-flight medical monitoring is focused on the assessment of the individual's cardiovascular and pulmonary function, as well as evaluation of overall physiological performance on the basis of blood work analysis, urinalyses, body mass, and body temperature measurements. In addition, a number of environmental tests are performed in-flight to ensure adequate spacecraft microflora, cabin toxicology, and atmospheric composition.

Table 7.2 depicts frequency of in-flight monitoring activities that are scheduled and periodic, other than during insertion, docking, and extravehicular activities (EVA), when the astronauts are monitored continuously.

More detailed review of in-flight medical monitoring and specifics of physiological data acquisition will be provided in the next chapter "Space as an Extreme Environment - Technical Considerations."

7.6 Terrestrial Application of Spaceflight Concepts

While outer space sounds so distinct, it shares many commonalities with terrestrial extreme environments. Extreme environments can be defined as those that are unnatural for human existence and "demand complex adaptation," characterized by conditions, such as confinement, isolation, and chronic exposure to stressors, all of which contribute to development and onset of negative medical contingencies, impacting health, performance and safety. A generalized framework of the effects of extreme environments on human adaptation is summarized in Fig. 3.1 in Chap. of this book.

Figure 7.4 demonstrates interconnectedness of human physiology and environmental factors, indicating the many aspects of human-technology interaction in extreme environmental conditions on Earth or in outer space. Human adaptation in extreme environments is affected by numerous factors, including physical conditions, crew characteristics, and mission objectives, as described in Fig. 7.4. Physical conditions include environmental temperature, gravity or weightlessness, weather conditions, as well as dark and light cycles. It can also include habitability factors, such as noise levels, available facilities and supplies for personal use.

Crew composition and characteristics are instruments in the success of the mission. A number of factors, including size, heterogeneity, expertise, and personalities need to be considered to ensure good group dynamics, adequate performance, safety and well-being of an entire crew.

Table 7.2 In-flight medical monitoring during long-duration flights on the Mir station [19]

Type	Instrument	Parameters	Data	Frequency
Medical monitoring during insertion and docking	Alpha-01	Cardiovascular function	Electro-cardiography	Continuously from insertion through docking
		Respiratory function	Pneumography	Continuously from insertion through docking
Medical monitoring during EVA	Beta-08	Cardiovascular function	Electro-cardiography	Continuously during EVA
		Respiratory function	Pneumography	Continuously during EVA
		Body temperature	Body temperature	Continuously during EVA
	Gamma-01, onboard cycle ergometer	Hand cycle ergometer	Arm muscle strength	10–15 days prior to EVA
In-flight medical monitoring	Gamma-01	Cardiovascular function	12-lead ECG	Every 30 days
	Gamma-01, Chibis pneumo-vacuum suit	Cardiovascular response to LBNP	ECG, blood pressure, rheoencephalo-graphy	Every 60 days
	Gamma-01, onboard cycle ergometer	Cardiovascular system response to graded physical load	ECG, blood pressure, rheoencephalo-graphy	Every 45 days
	Body mass measurement device	Body mass	Body weight	Every 10 days
	Plethysmograph	Calf volume	Calf volume change	Every 10 days
	Reflotron	Blood chemistry	Hemoglobin, glucose, triglycerides, cholesterol, bilirubin, amylase, alanine, etc.	Every 90 days
	UBIM-9	Urine chemistry	pH, protein, glucose, red blood cells, leukocytes, etc.	Every 30 days

(continued)

Table 7.2 (continued)

Type	Instrument	Parameters	Data	Frequency
	Spacelab ECG	24-hour Holter monitoring	ECG using 2-leads over 24-hour period	Every 60 days
	Treadmill and cardiocassette for ECG recording	Effectiveness of physical training	ECG, workload	Every 60 days
	M-1100, Hematocrit	Hematocrit	Ratio of plasma to packed cells	Every 30 days
	FBM-01 filter pump	Environmental monitoring	Spacecraft microflora	Every 60 days
	Environmental sampler	Formation of microbial colonies	bacterial and fungal flora of the habitat	Every 60 days
	Audiometer-2	Noise level parameters	Spacecraft acoustics	Every 60 days
	Aspirator AM-5	Spacecraft atmospheric contamination	Atmospheric toxicology	Every 60 days

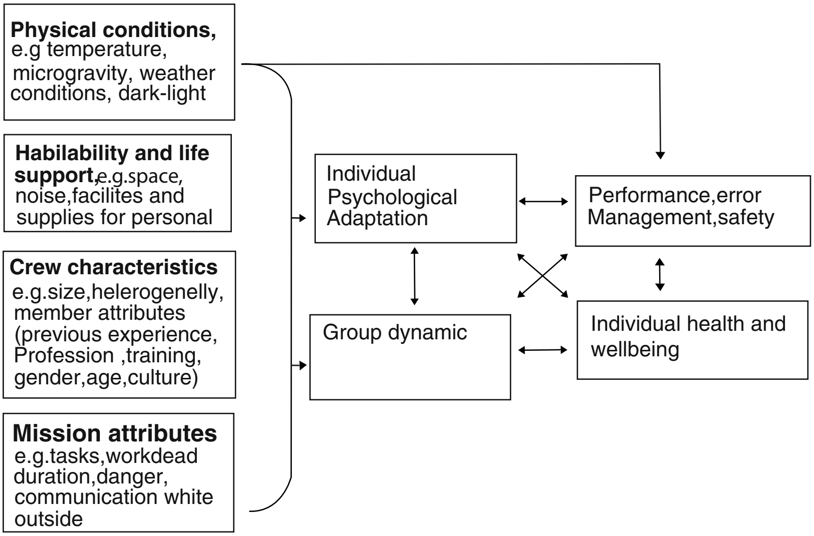

Fig. 7.4 Factors affecting human adaptation in ICE environments [23]

The objectives of the mission are typically established in such a way, so as to complete the necessary tasks/workload, while schedule meaningful activities for the crew, including communication with the outside world, to ensure psychological and physical well-being of the crew.

In conclusion, technological advancements have pushed the boundaries of biological and environmental limits by supporting and preserving human life in extraordinary conditions [27]. It enabled creation and maintenance of a desirable ecosystem within extreme environments, in which humans can adequately adapt and preserve optimal occupational performance. The various aspects of human adaptation to extreme environments and means of its evaluation will be presented in the chapter to follow.

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Chapter 8
Space as an Extreme Environment: Technical Considerations

Anastasiia Prysyazhnyuk and Carolyn McGregor AM

8.1 Introduction

The space environment is truly a unique habitat for the humankind, allowing the human mind to wander to and explore what was once unthought of. It puts to test the boundaries of the human mind and body, while approbating the critical thinking and performance under extremely dangerous, life-threatening conditions.

The previous chapter on space as an extreme environment considered the uniqueness of the space environment and its impact on performance and overall functionality of body systems. Next, it is important to consider human in a loop, reviewing the closed-loop systems on the International Space Station (ISS) that ensure habitability, safety, and comfort to support manned in-orbit scientific exploration.

The International Space Station (ISS) is the largest orbital laboratory in the human history. Launched on November 20, 1998, the main contributors are the space agencies of the USA, Canada, Russia, Europe, and Japan [1]. As of 2015, over 220 astronauts have lived on the ISS for various periods of time, the longest being 342 continuous days spent in space by the American astronaut, Scott Kelly and Russian cosmonaut, Mikhail Korniyenko, as part of the one-year mission [1, 2]. The missions of such long duration provide beneficial insights into the long-term effects

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of the spaceflight environment and reveal medical, psychological, and biomedical challenges experienced during spaceflight [1].

8.1.1 Structure of the ISS

The ISS consists of a series of modules that house personal-use facilities, individual sleep compartments, exercise and research facilities and the service module [1]. A total of six astronauts/cosmonauts can inhabit the ISS at any one time. While a detailed architecture review of each of the modules is beyond the scope of this chapter, a main emphasis will be placed on the Crew Health Care System (CHeCS), also known as the Integrated Medical System.

CHeCS is a multi-tier system that integrates various ISS hardware components to ensure adequate environmental conditions to support health and safety of the crew during long-term missions. CHeCS consists of three sub-systems, which are the countermeasure system (CMS), the environmental health system (EHS), and the health maintenance system (HMS) [1].

The countermeasure system consists of a series of individualized protocols aimed at alleviation of the deleterious effects of the spaceflight environment, instituted through a series of exercise regimes. The CMS supports monitoring of the crew's physiology during exercise regimes, enabling fitness evaluations [1]. The CMS hardware components are made up of exercise equipment and biomedical monitoring devices. The exercise equipment includes a treadmill, cycle ergometer, and resistive exercise device [5]. Biomedical monitoring hardware consists of a heart rate monitor, blood pressure and electrocardiogram monitor and a portable computer to store and analyze the acquired physiological data [5].

The environmental health system (EHS) monitors and evaluates various aspects of the space station environment, including cabin toxicology, radiation and solar flares exposure, water quality, and microbial contamination [1]. In addition, other environmental parameters such as the leak detection assessment, temperature, pressure, relative humidity, light level and acoustic level monitoring is also performed [3, 5].

The health maintenance system (HMS) represents the in-flight medical capacity, ranging from health monitoring and therapeutic medical care to in-flight life support and resuscitation [1]. In-flight physiological monitoring consists of assessment of the heart rate, electroencephalogram (EEG), electrocardiogram (ECG), respiration rate, blood pressure, pulse rate, pulse oximetry, body temperature, glucose levels, and caloric expenditure [3].

Each of the CHeCS sub-systems represents a complex technological network, required to execute a series of tests and assessments to ensure habitability of the space station and well-being of its crew members. Further sub-sections will consider the health maintenance system, as the foundation of the in-flight medical system to ensure adequate performance of the crew and successful execution of mission objectives. The goal of such a system is to mitigate the risks and ensure successful

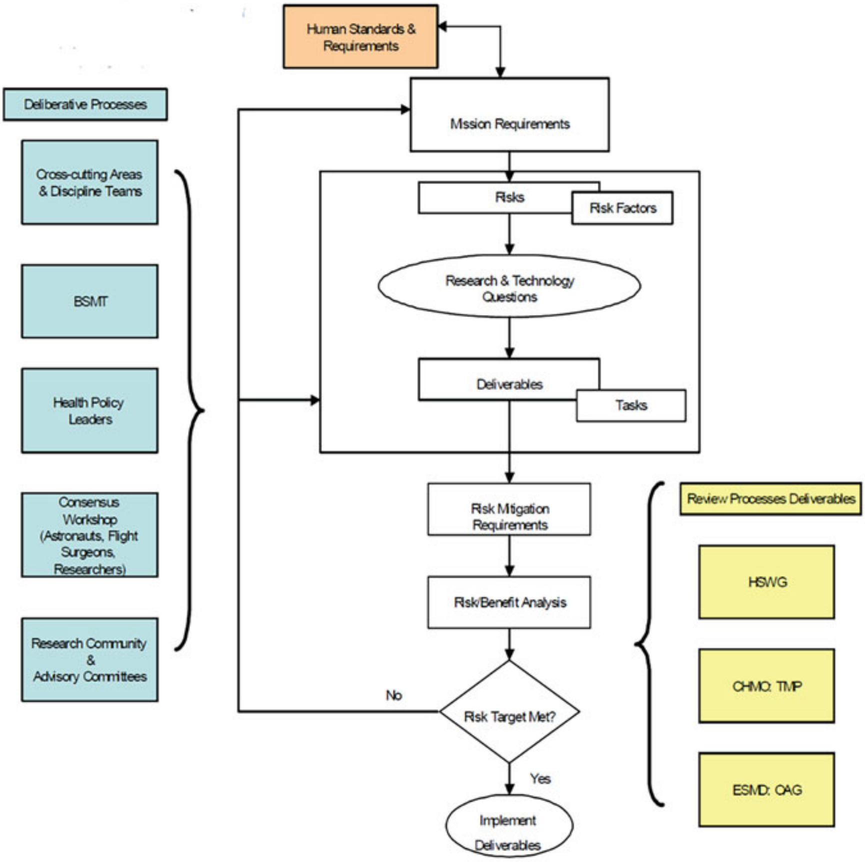


Fig. 8.1 Risk identification and mitigation process flowchart [6]

reduction of adverse outcomes through research and development of technological solutions [6].

The process flow chart represented in Fig. 8.1 outlines the process of risk identification and assessment, used as a guideline to inform medical standards aboard the space station. The roadmap defines a risk "as the conditional probability of an adverse event from exposure to the space flight environment," while a risk factor is defined "as a predisposing condition that contributes to an adverse outcome" [6]. The time and course of the intervention is directly related to the severity of the outcome. It has been shown that intervention at the risk factor level can greatly reduce the risk of developing adverse outcomes [6]. The abbreviations within the figure are explained as the following, BSMT (Bioastronautics Science Management Team), HSWG (The Human System Working Group), CHMO (The Chief Health and Medical Officer), ESMD (The Exploration Systems Mission Directorate), TMP (transition to medical practice), and OAG (Operations advisory group). The transdisciplinary team involved in deliberation and review process highlights the multi-disciplinary nature of human participation in scientific exploration, which requires rigorous assessment and evaluation to ensure all possible risks and potential outcomes have been considered and the necessary measures are applied to preserve and maintain health of the crew.

Prior research identified three main categories of risk assessment/mitigation during spaceflight and they can be defined as the “resolution with minimal or no intervention; fatal incidence unless response applied; fatal incidence regardless of intervention efforts” [8].

This chapter will consider medical capacity aboard the space station, reviewing the current digital health technologies and future capabilities to further enhance health monitoring of astronauts to alleviate onset of adverse outcomes. The significance of technological capabilities will be amplified as we consider deep space exploration and missions of much longer durations.

8.2 Data Frequency for Meaningful Use

Technological advancements continue to redefine the standards of data sampling to ensure the acquired data can be used in a meaningful way. Early models of portable Holter-style monitoring devices, such as Cosmocard, continue to be used in space by the Russian cosmonauts, for acquisition of an electrocardiogram signal. The medical standard for ECG signal sampling rate for an adult population is 250 Hz, equivalent to 250 readings a second [12]. Further down sampling of the ECG signal to 100 Hz is still acceptable for time-domain analysis, yet insufficient for the frequency-domain analysis [12]. The Cosmocard device down samples the acquired data, as it derives the heart rate and its various variability indices at a frequency of 1 Hz, which is equivalent to one reading per second. The clinical data acquisition by the Cosmocard device is scheduled and discontinuous, greatly impacting meaningful use of the data to support diagnostic monitoring and clinical decision making.

Numerous algorithms have been developed for heart rate variability analysis to support meaningful use of the acquired data and to overcome the challenges of limited and discontinuous clinical data availability. Baevsky et al. developed the functional health state algorithm, which has been used as a “measure of wellness” over the last couple of decades. The algorithm down samples the ECG signal to a two-dimensional tuple, which has a frequency of a tuple every 5 min. Subsequently, such tuples are down sampled even further to provide an average hourly or daily reading. However, recent research has demonstrated that down sampling of the signal results in a tremendous amount of data loss, hindering the ability for early detection monitoring and inability to identify the trajectory of health state changes that occur [7, 9, 15, 16]. As such, the use of alternative technologies continues to be explored to enhance health monitoring capacity aboard the space station.

The Canadian Space Agency has deployed the first biomedical monitoring garment, known as the Astroskin/Bio-Monitor aboard the ISS as of December 2018. Astroskin has the capacity to support continuous biomedical monitoring and real-time data acquisition, improving data accessibility and use to inform medical care and counter measure regimes during the same mission, contrary to the retrospective approach that is still in-use on the ISS with other biomedical monitoring modalities. The Bio-Monitor supports the acquisition of the astronaut's vital signs, including pulse, electrical activity of the heart, blood pressure, breathing rate and volume, skin temperature, blood oxygen saturation, and physical activity levels [10]. The Bio-Monitor records a large volume of physiological data, offering more than 42,000 data points per minute. Its data sampling rates for ECG is 256 Hz, while the thoracic and abdominal breathing rates are measured at 128 Hz each, 3-axis acceleration at 64 Hz, blood pressure at 1 Hz, and skin temperature at 1 Hz, greatly enhancing the amount and quality of the acquired physiological data [11]. While detailed review of medical standards for physiological data acquisition aboard the ISS is beyond the scope of this chapter, this section offers appreciation for the desired data sampling frequency required for meaningful use of the acquired data. In sections to follow, technological capabilities of biomedical monitoring modalities and the required network topologies to support medical care aboard the ISS will be considered.

8.3 Technologies for Data Collection

A conceptual model of Space Station Health Maintenance Facility is represented in Fig. 8.2, which dates back to the early days of human space flight when space missions were of short duration and return to Earth upon an emergency was possible [4]. It was then when the missions of longer durations were planned and the Space Station was in the process of being assembled. As the missions evolved in complexity and increased in duration, the medical capacity aboard the station became one of the top priorities for Government agencies, as the health risks associated with prolonged exposure to conditions of spaceflight significantly increased.

Figure 8.2 displays a restrained patient surrounded by medical support equipment, including dental instruments, pulse oximeter, a ventilator, suction, and air fluid separator, IV pumps, patient monitor, defibrillator, IV fluid production and support system, computer and a medical information system, as well as diagnostic imaging modalities, pharmacological kit, microbiology and clinical laboratory station [4].

The conceptual model of the health maintenance system represented in Fig. 8.2 outlined the crucial elements required to diagnose and treat minor injury and respond to emergency situations aboard the space station [4]. It was also used to inform the guidelines for medical care and expertise required to perform minor emergency medical and surgical procedures. A vital element of the HMS was a computerized medical decision support system that could integrate data acquired

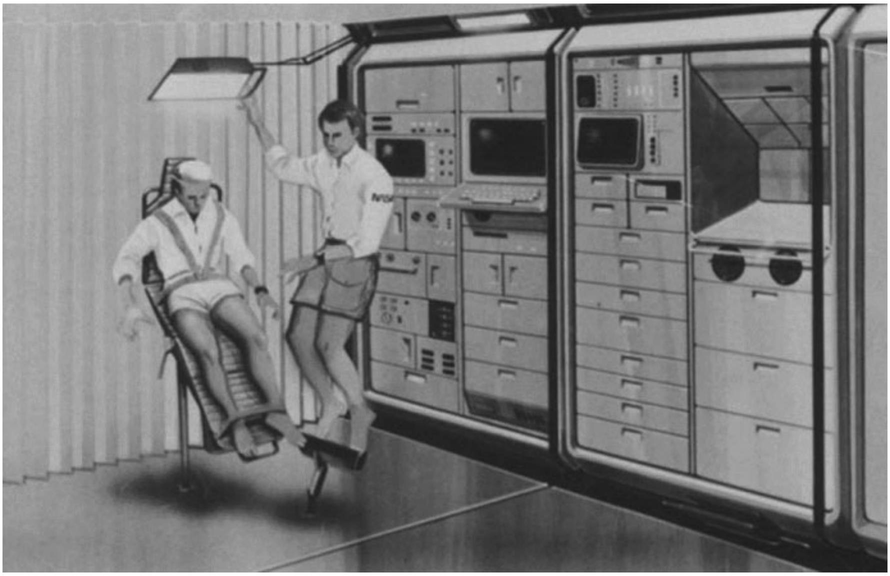
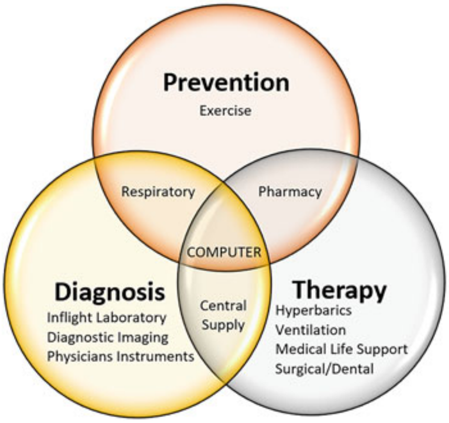


Fig. 8.2 Conceptual model of the Space Station Health Maintenance Facility [4]

Fig. 8.3 The capabilities of computerized medical decision support system at the Space Station recreated from [4]



from the various medical equipment modalities, while most of the clinical decision support capabilities were outsourced to terrestrial mission control centers [4].

The capabilities of the medical decision support system are schematically summarized in Fig. 8.3. The figure represents the decision support system at the center of prevention, diagnosis, and treatment(therapy) of medical contingencies aboard the Space Station. It integrates the various inputs of physiological data to identify and mitigate health risks in a timely and effective manner, so as to preserve the well-being of space crew.

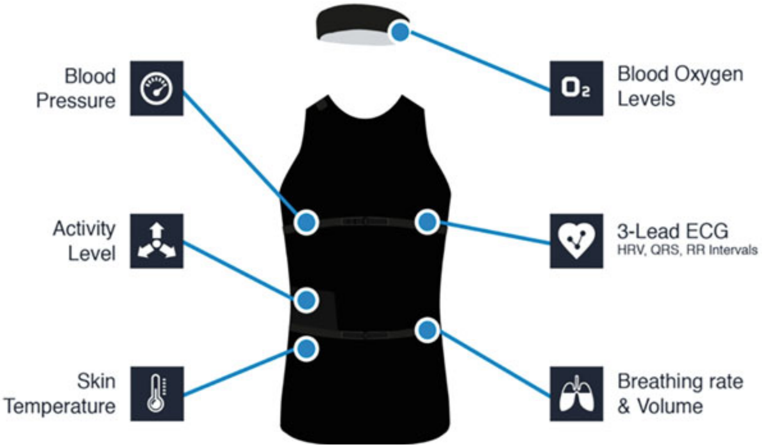


Fig. 8.4 Astroskin biomedical monitoring garment [11]

Over the last half a century, the onboard medical capacity has evolved from a very limited medical kit, consisting of a few medications and infantile medical monitoring devices, to sophisticated wearable biomonitoring garments, advanced life support hardware, and a more inclusive medicine cabinet [5].

Biomedical monitoring equipment evolved from collect and store devices, such as the portable Holter-style ECG monitoring devices to non-invasive biomedical monitoring garments, such as the Astroskin, visualized in Fig. 8.4, to support real-time data acquisition and transmission [9], further enhancing the onboard medical capacity and shifting towards autonomous, personalized medical care.

Rapid technological advancements have enabled modernization of biomedical monitoring modalities to respond to the specifics of the spaceflight environment, including miniaturized, non-invasive, wearable and/or wireless, easy to use devices that create no or minimal discomfort during data collection [22], while supporting continuous data acquisition with the capacity for real-time data transmission.

Despite decades of technological research and development, the capacity of the medical decision support system aboard the space station is still very limited, while a significant amount of analytics is performed retrospectively, upon return to Earth [9], necessitating further research to support the growing spaceflight medical care demands, especially as humans embark on missions of longer distance and duration.

8.4 Methods to Acquire Data from Wearable Devices

Space communication networks are the foundation of nearly all processes and functional domains within the spacecraft, including intra-vehicle, inter-vehicle, and planetary surface activities [3]. Each of the functional domains comprises numerous applications, which can support acquisition of data at various rates and ranges, an overview of which is summarized in Table 8.1 [3].

As seen in Fig. 8.2, a wide variety of biomedical monitoring and life support devices make up the onboard health monitoring system. These devices have various

Table 8.1 Key application areas for functional space communication domains [3]

Functional domain	Application areas	Number of nodes	Data rate	Range	Applicable standards
Intra-vehicle	Inventory monitoring	100 s	Very low	<10 m	IOS, 18000-6C, EPCglobal
	Environmental monitoring (i.e., temperature, pressure, humidity, radiation, water quality)	10 s to 100 s	Low to medium	< 100 m	802.15.4, 802.15.4e, ISA100.11a
	Physiological monitoring (including EVA suit biomedical monitoring)	1 s to 10 s	Low to medium	<100 m	802.15.1, 802.15.4, 802.15.4e, ISA100.11a
	Crew member location tracking	1 s to 10 s	Medium to high	<300 m	802.11, 802.15.3, 802.15.4, 802.16, LTE
	Structural monitoring	10 s	Medium to high	<300 m	802.11, 802.15.3
	Intra-spacecraft communication (Voice and video)	10s	Medium to high	<300 m	802.15.1, 802.11, 802.18, LTE
	Process monitoring and automated control and scientific monitoring and control	10 s to 100 s	Low to high	<300 m	802.15.3, 802.15.4, 802.15.4e, ISA100.11a, 802.11, 802.16, LTE
	Retro-fit of existing vehicle with new capabilities	10 s to 100 s	Low to high	10 m–100 km	802.15.3, 802.15.4, 802.15.4e, 802.11, 802.16, LTE
AIT activities	Spacecraft assembly, integration and test	10 s to 100 s	Medium	<100 m	802.15.3, 802.15.4, 802.15.4e, ISA100.11a, 802.11
Inter-vehicle	Inter-spacecraft communication (Voice, video and data)	10 s	High to extremely high	1 m to 100 km	802.16, LTE, Prox-1, AOS

(continued)

Table 8.1 (continued)

Functional domain	Application areas	Number of nodes	Data rate	Range	Applicable standards
Planetary surface	IVA-EVA, EVA-EVA, Habitat to LRV, LRV-crew communications (voice, video and data)	10 s	Medium to high	1 m–50 km	802.11, 802.16, LTE
	Robotic operations	10 s	Low to high	1 m–50 km	802.15.3, 802.15.4, 802.11, 802.16, LTE
Orbit relay to surface	Surface-to-orbit communication (voice, video and data)	10 s	High to extremely high	>200 km	LTE, Prox-1, AOS

modes of connectivity that enables the transfer of the acquired data from the device to onboard medical system. The modes of connectivity include wired, Bluetooth, and Wi-Fi connection. Wired connectivity is still an existing limitation of data acquisition aboard the spacecraft, as it limits the functionality of biomonitoring devices as store and collect devices. Bluetooth data transmission requires one to one connection greatly impacting its usability and practicality, especially in an application such as biomedical monitoring. While a review of specifics of different data acquisition modalities is beyond the scope of this chapter, the main emphasis will be placed on wireless mode of data acquisition, which will be discussed in greater detail below, as this is the direction technology that is evolving in.

8.4.1 Health Monitoring Networks

Tremendous progress has been made as the data acquisition modalities evolved from wired to Bluetooth to wireless modes of data acquisition and transmission, which provided greater flexibility and robustness of data collection, improved power management and user-operability, all while enhancing the accessibility and usability of the acquired data.

Spacecraft wireless health monitoring network is schematically represented in Fig. 8.5. As opposed to the conventional avionics network, the wireless network provides robustness of data acquisition, flexibility, and redundancy [3]. It has many advantages over the other modes of data acquisition, including its own power source to supply the sensor, greater receiver sensitivity and low-weight. However, its functionality is highly dependent on the average power consumption of the unit, directly related to the lifetime of a battery [3].

The key applications of spaceflight communication domains that fall under the mandate of CHeCS system include environmental and physiological monitoring,

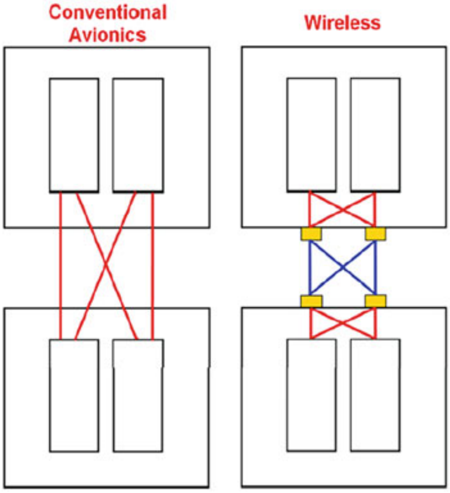


Fig. 8.5 Schematic representation of spaceflight wireless health networks [3]

both of which deal with low to medium data rate wireless interfaces and ranges of data acquisition of less than 100 m, Table 8.1, [3]. The wireless networks of environmental parameters include tens and hundreds of nodes, while networks of physiological parameters are comprised only of up to ten individual nodes. The number of nodes of each of the wireless sensor networks further informs the routing protocols and specifies the requirements for network topology to provide Quality of Service assurance and effective management of data traffic diversity [3].

8.4.2 *Biomedical Decision Support System*

Biomedical decision support system consists of multiple network topologies that enable interoperability of biomedical sensors and devices. Its layer protocol provides network applicability, reliability, scalability, and longevity, all while supporting the required level of technology readiness and compliance with international standards. It deals with diverse types of data, including voice, video, physiological waveforms, and other biomedical data streams to support scheduled and ad-hoc medical assessments within the spacecraft [3]. The network attributes of data rates may vary from medium ($1\,\frac{\mathrm{mb}}{\mathrm{s}}$) for physiological variables, such as EEG, ECG, HR, and BP, to high ($>\ 1\,\frac{\mathrm{mb}}{\mathrm{s}}$) for video and other diagnostic imaging modalities. Biomedical data is typically generated at high rates, while the wireless networks that route the data consist of low number of nodes [3].

While there may exist a number of similarities in environmental and biomedical spaceflight wireless networks, the major differences are in the types of data being carried by those networks. Biomedical data may include routine non-critical data and vital emergency medical information. It is important to note that criticality of the data may change in an instant, as a result of environmental, psychological, or physiological circumstances. As such, it is of crucial significance for the biomedical decision support system to be able to promptly respond in an emergency situation and have the capacity to prioritize dynamic data flow in the order with the circumstances. Furthermore, biomedical data is extremely time sensitive, on the order of milliseconds, which may contribute to early diagnosis of pathological conditions or make a difference in crew survival or loss of life [3]. Thus, it is essential for a spaceflight biomedical decision support system to have a high level of autonomy and self-sufficiency, so as to operate effectively with minimal required interaction from the crew.

8.5 Data Transmission to Onboard Systems and Mission Control

Data transmission from various biomedical and environmental monitoring modalities to the onboard interface is a part of a complex network architecture, an example of which is known as the Spacecraft Onboard Interface Services (SOIS), schematically represented in Fig. 8.6. SOIS is provisioned through a multi-layered topology, which includes user applications, network management services, and plug-and-play services [3]. Each of the layers has multiple sub-layers to ensure the Quality of Services and includes the application support layer, transfer layer, and sub-network layer. Sub-network layer represents different modalities of data links, including various types of wired (ethernet, space wire, USB, etc.) and wireless connections. The sub-network layer is further responsible for generic data convergence, storage and temporal validation of the acquired data that can be further transferred to the application support layer for data prioritization, analysis, and storage.

8.5.1 Onboard Biomedical Monitoring Network Architecture

It is important to note that SOIS architecture represented in Fig. 8.6 is not exclusive but rather one of the examples of the interfaces of the onboard medical systems. Another example of space crew health monitoring network architecture utilizing the VPack biomedical sensor system is summarized in Fig. 8.7. The VPack biomedical monitoring system has been designed for the intra-vehicle (EVA suit) and planetary surface activities by providing a computerized platform with biomedical sensors to support continuous physiological monitoring of the crew [8]. It also represents a multi-layer topology, including data sampling, pre-processing, archiving, data analysis and results presentation components. Figure 8.7 shows a wired mode of data acquisition, which was chosen in order to capture data at a steady rate of

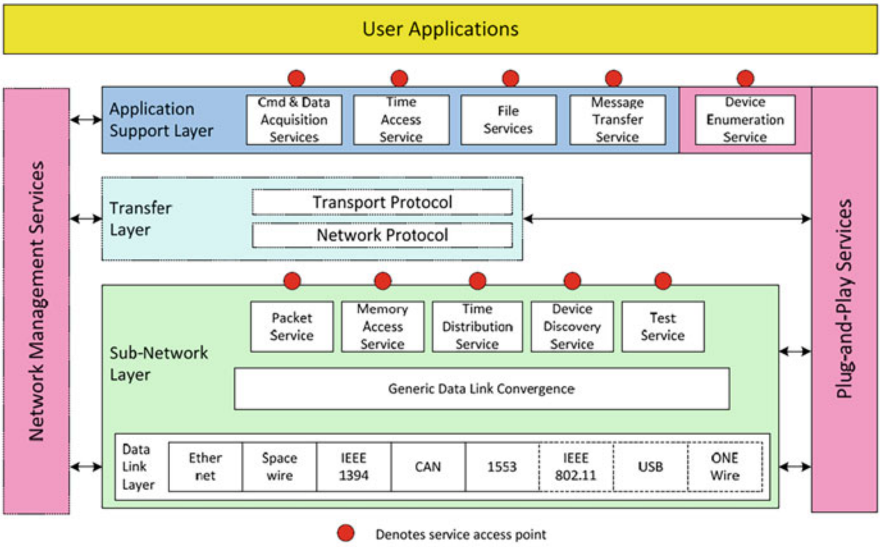


Fig. 8.6 The Spacecraft Onboard Interface Service (SOIS) architecture from [3]

100 samples per second, with the exception of pulse oximeter, for which data was captured in an analog format. The acquired data is then subjected to pre-processing in the Sensor Processor module, where it goes through various filters and amplifiers to generate the desired spectrum of values, data packets of which are then routed to a customizable computer system interface (CAI). The CAI interface is further utilized for data archive, analysis, and results generation (not shown on Fig. 8.7).

While Figs. 8.6 and 8.7 only provide a snapshot of the possible network architectures utilized for the onboard biomedical monitoring system, it offers an appreciation for the complexity of the architecture required to integrate inputs from various biomedical monitoring modalities, while ensuring a steady and consistent rate of data acquisition for meaningful use of physiological data, which can support early detection monitoring, primary, preventative, and emergency care aboard the spacecraft.

8.5.2 *Data Transfer to Mission Control Centers*

Data transfer to terrestrial mission control centres mostly relies on two-way telemetry downlinks. The usability and applicability of this approach, should an emergency situation arise, would be greatly impacted by missions of longer distance and duration, where the delay in data transmission will be significant and incompatible with the goal of providing timely recommendations. It further highlights the need for development of a universal biomedical decision support system with the capacity

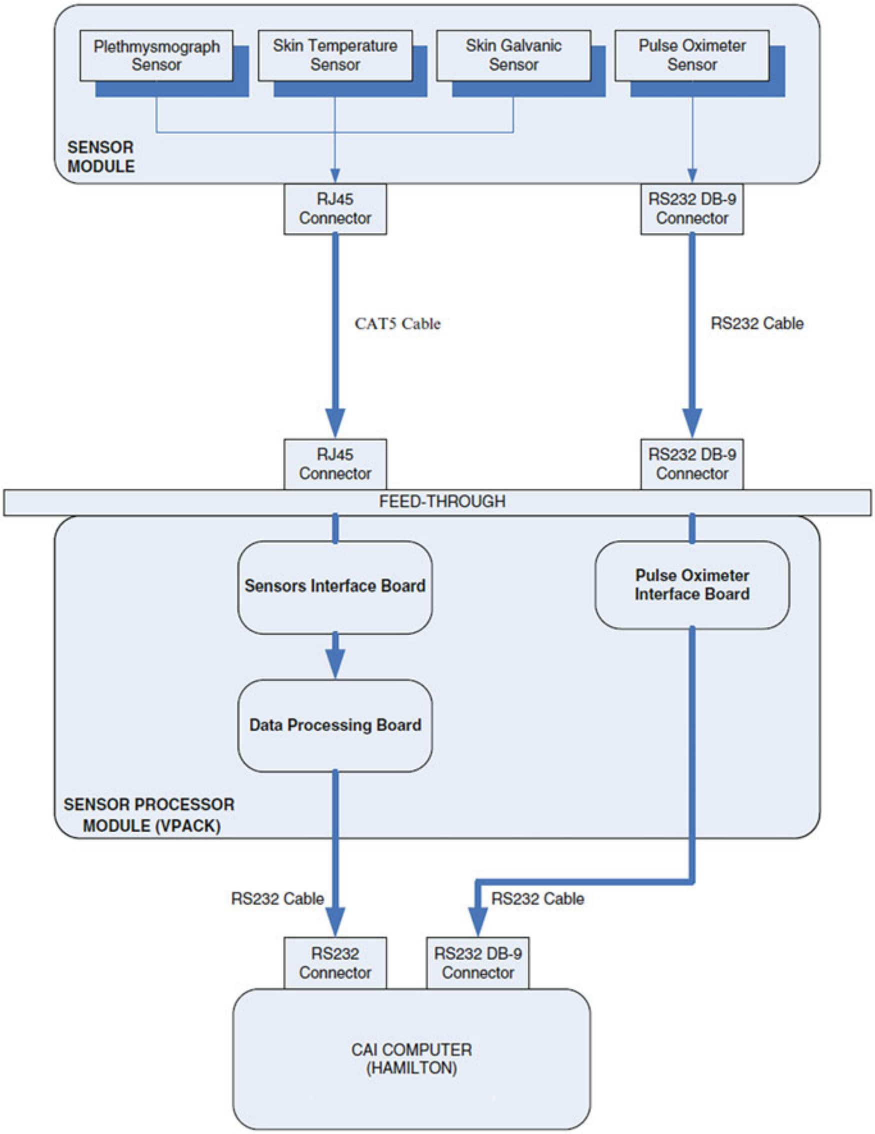


Fig. 8.7 Schematic representation of space crew health monitoring system utilizing the VPack biomedical sensor system [8]

to integrate all available physiological, activity, and environmental data to inform clinical decision making, with the ability to support autonomous functionality of the system and provide real-time feedback. A prototype of such a system, known as Artemis, has been previously proposed and will be discussed in greater detail in sections to follow.

8.6 Real-Time Analytics Platforms

Existing biomedical monitoring systems in-use on the International Space Station support routine nominal health assessments, as well as primary and emergency medical care. Despite decades of technological research and development the majority of data analytics are performed retrospectively, upon return to Earth. As such, meaningful use of the acquired data is limited by the lack of appropriate technological solutions to support real-time data acquisition and analytics to inform development of personalized regimes to maintain health and well-being of the crew during the mission. All space agencies with a priority area of astronaut health have recognized that this is not a sustainable paradigm when supporting long range missions and missions outside of low Earth orbit (LEO).

The Canadian Space Agency previously proposed an Advanced Crew Medical System (ACMS) to provision a Space Medicine Decision Support System [23]. A conceptual diagram of an Advanced Crew Medical System is presented in Fig. 8.8.

The ACMS is made up of Input, Output, and Data Processing and Handling components [23]. The Pre-flight medical history and In-Flight information such as non-medical data, together with medical data from medical devices, clinical observations and personal assessments are collected within the Input component. The Data Processing and Handling Component processes all data received for the Output component to create information and knowledge. The Output component enables the generation of the following outputs:

1. Astronaut medical telemetry and health status
2. Diagnosis
3. Recommended treatment/countermeasures
4. Data archiving suitable for research
5. Medical consumables management

The ACMS conceptual diagram proposes that all data is forwarded to an Electronic Medical Record database from which a Decision Engine would then work to analyze the data using medical knowledge contained in the Medical Knowledge database to support Diagnosis Treatment Procedures and Health State Monitoring and Prognostics. The Medical Knowledge database would be updated by the ACMS Operations and Maintenance database.

An innovative Big Data analytics platform, known as Artemis, has been previously proposed by McGregor [13], to address existing challenges and limitations of biomedical health monitoring during spaceflight. Artemis is a middleware platform provisioned through seven components responsible for data collection, transmission, online analytics, stream persistency, knowledge discovery, (re)deployment, and results presentation, schematically illustrated in Fig. 8.9.

The data collection component supports concurrent acquisition of physiological, activity, and environmental data from numerous biomedical monitoring and environmental sensor modalities through various modes of connectivity, including

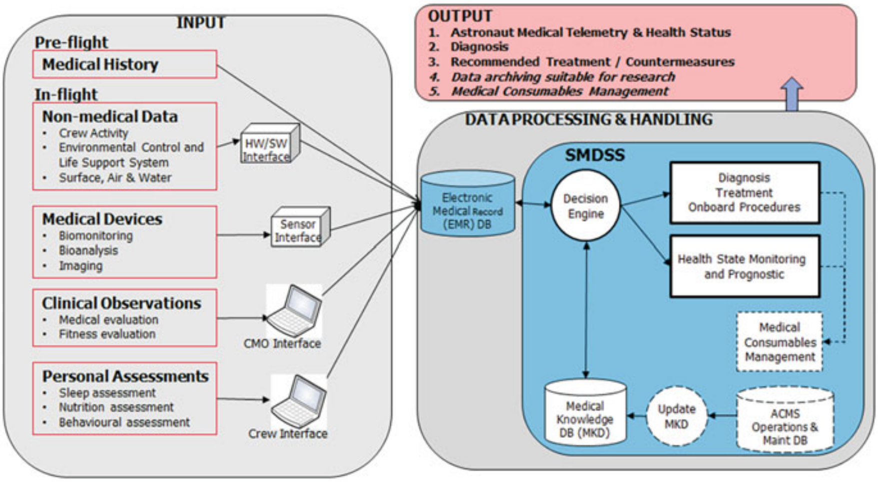


Fig. 8.8 Conceptual diagram of an Advanced Crew Medical System [23]

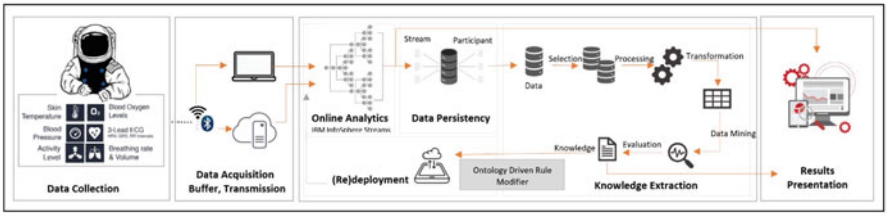


Fig. 8.9 Artemis architecture for online health analytics during spaceflight [7]

wired (Ethernet, USB, etc.), Bluetooth, and Wi-Fi. Subsequently, the data can be transmitted for real-time data analytics or stored for retrospective use.

Online analytics component utilizes IBM InfoSphere Streams, in which numerous algorithms are being deployed. Algorithms are written in streams programming language, also known as stream graphs, to support analytics of high volume and high frequency physiological data streams, numeric waveforms, and other types of relevant data.

The data persistency component ensures that acquired and derived data is continuously being stored to support prospective and retrospective analytics and clinical research.

The knowledge extraction component screens and analyzes stored and incoming data streams to identify new physiological patterns that are associated with clinical conditions. It is used to develop and validate new algorithms for relevant physiological behaviors. Once validated, new algorithms can be deployed through the (re)deployment component to support revised/updated analytics during the same mission.

The results presentation component provides the necessary framework to support visualization of raw and derived physiological data that can be viewed in real-time and retrospectively by those aboard the spacecraft or at terrestrial Mission Control Centers. The potential of this approach has been demonstrated in collaboration with the Russian IBMP as a design [15] and through two analogue mission experiments: Luna 2015 and the 2016 dry immersion experiments [7, 15, 16, 19].

The ACMS conceptual design while providing a wholistic approach for space medicine decision support does not enable streaming analytics. Big Data streaming analytics, such as that which is proposed by Artemis, utilises the Internet of Things paradigm. It has great potential to enable diagnosis, treatment and on-board procedures together with real-time health state monitoring and prognostics to run in real-time before data persistence.

8.7 Algorithms for the Assessment of Health, Wellness, Resilience, and Adaptation

Extensive terrestrial research has demonstrated that human body is able to effectively adapt to various extreme environmental conditions, while maintaining the desired level of wellness, as described in the previous chapter.

Decades of human physiology research have been aimed at development of methods and strategies to develop resilience, while effectively evaluating adaptation capacity of the human body. Traditional approaches to the observation of astronauts during a space mission assess physiological and mental health discontinuously through periodic health checks, examinations, and checklists.

Health assessment follows terrestrial guidelines based on differential diagnosis and known pathophysiologies of disease. Current directions for autonomous health monitoring in space is to enable the creation of knowledge-based systems based on this differential diagnosis and disease pathophysiology information. This has been linked to the Star Trek tricorder and many challenge competitions have emerged to create such a device/system.

Assessment of adaption response is predominantly performed through retrospective research [9]. Resilience development to the impact of space and the resulting adaption response is provided through the use of countermeasure exercise and operational equipment for use by the astronauts during space missions. Currently, real-time assessment of the impact of resilience development during space missions is not available.

The functional state algorithm proposed by Baevsky [18] provides an assessment of wellness and adaption for Russian cosmonauts through the assessment of various features within an electrocardiogram signal. Time and frequency domain heart rate variability (HRV) parameters are used for computation of two canonical variables (L1 and L2) retrospectively on Earth. These measures are derived on 5 min windows

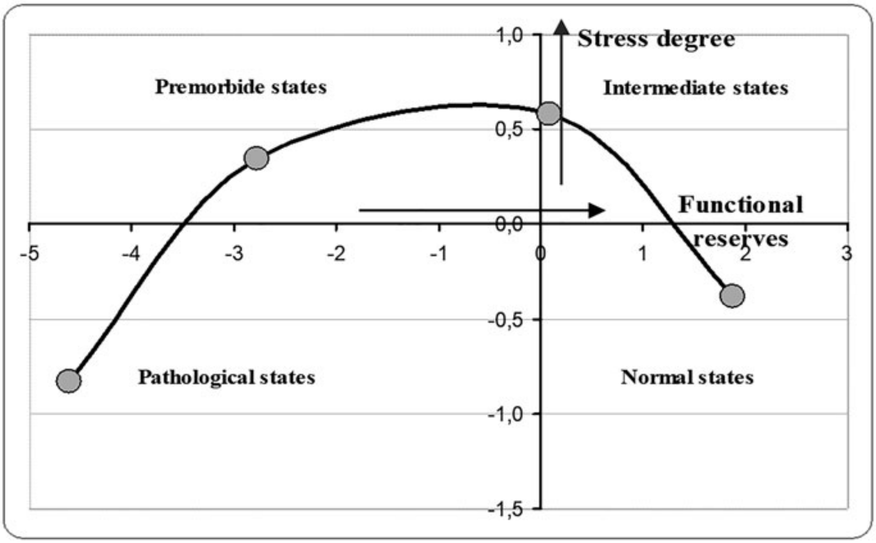


Fig. 8.10 Baevsky's phase plane of functional health states [18]

of ECG data and the L1 and L2 are averaged over the day to derive a daily score (Fig. 8.10).

The L1 and L2 values are used in combination to derive a functional states location within the phase plane of coordinates. The normal physiological state is reflected in the lower right quadrant with positive L1 and negative L2 values. In this state, the body has functional reserves and is not under stress. A rise in the degree of stress translates to an increased value of L2. Positive L1 and L2 values are referred to as the "intermediate" state, also known as prenosological, and are located in the upper right quadrant. When functional reserves are depleted transition towards the upper left quadrant, known as the premorbid quadrant, occur. In this state the potential to develop a new pathological state is more likely. Located in the lower left quadrant, negative L1 and L2 values are associated with the state of pathology where the development of clinical conditions are apparent.

This method has been shown to effectively predict the deviation from the state of norm and onset of pathological conditions in various terrestrial habitats, as well as during space travel. The functional health states are mathematically computed on the basis of two canonical variables that evaluate the amount of body systems tension and the level of available functional reserve to preserve the state of homeostasis. This method has also identified two transitional states between health and disease, denoted as prenosological and premorbid states, mostly differentiated on the basis of available functional reserves. This approach has been used by Russian cosmonauts aboard the ISS to identify early hallmarks of maladaptation and inform the course of required intervention.

The overall health condition of astronauts during a space mission requires a wholistic assessment across many dimensions. McGregor [14] proposed through transdisciplinary innovation across health and wellness in critical care, space, and tactical operators, a wholistic precision public health approach to health. She proposed an approach to health monitoring that assesses health, wellness, resilience, and adaption.

Various counter measure equipment are located on the ISS to assist the astronauts in mitigating the impact of space flight on their bodies. Current approaches to the assessment of adaption and deviation from homeostasis do not enable the integration of counter measure data either in the immediate term post use of the equipment or longitudinally from trend assessment [20, 21]. Further long range missions and missions beyond LEO will require an integration of countermeasure data with health monitoring data.

8.8 Data Persistence

Data persistence is becoming an essential aspect of a health maintenance system as the era of deep space exploration begins. It is of utmost significance to ensure technology readiness to support acquisition of multi-stream physiological, environmental, and activity data, all while ensuring its accessibility, validity, and compatibility to support real-time and retrospective analytics. As such, its paramount to put in place a comprehensive medical system architecture aboard the space station to ensure continuous storage of acquired and derived data to support data analytics.

Currently data persistence of astronaut health data occurs on Earth. From an ongoing operational health perspective, Earth based flight surgeons oversee the health of astronauts on the ISS. Medical records resulting from this care are maintained on Earth by the space agency from which the astronaut is based.

From a clinical research perspective, additional data has been captured since the first manned space flights to enable research on the human adaption process during space flight. While data for these studies has been collected during space flight, analysis, and storage of the data has occurred terrestrially back on Earth [9]. Data has been delivered back to Earth on various storage mechanisms and over recent years, for example, the Russian IBMP has transported data via USB drives during transports from the ISS.

Bio-Monitor Astroskin has developed a research platform that performs data analytics and supports data visualization in a dashboard format, enabling astronauts to visualize vital signs trends with an iOS app or computer interface. The Astroskin research platform is still in early stages of development and does pose some compatibility issues for use in space necessitating further research and technology development. The analytics provided on the ISS from the data acquired by the Astroskin is still in its infancy.

Extensive research performed in terrestrial simulation environments and aboard the space station has identified the need for development of a data warehouse onboard the space station to support longer range missions so that trends can be easily tracked with proactive alerting.

8.9 Secondary Use of Data

Biomedical data collection during spaceflight presents great potential for terrestrial application in various extreme environments, including but not limited to military, navy, sub-marine, first responders, tactical operators, arctic and Antarctic expeditors, and many other occupations discussed within the context of this book that are exposed to various occupational stressors for prolonged periods of time. Extreme environmental conditions test the adaptation mechanisms of the human body to varying degrees, informing development of resilience strategies to preserve well-being will alleviate deleterious effects associated with various extreme environmental conditions.

8.10 Knowledge Discovery

Knowledge discovery is an important functional requirement for health, wellness, resilience, and adaption research in space. The current paradigm for knowledge discovery relating to health, wellness, resilience, and adaption research on astronauts is to forward the data to Earth and perform the analysis retrospectively [9]. For long range missions, it is imperative that functionality for knowledge discovery in relation to health, wellness, resilience, and adaption can be performed on the spacecraft, during the mission. This component would enable predictive health monitoring and early detection of pathophysiologies, which would provide the necessary data for clinical decision making should an illness or medical emergency occur aboard the spacecraft. In addition, it will ensure technology readiness to support prognostic health alert systems, thereby enabling early intervention and alleviation of adverse outcomes associated with conditions of spaceflight environments, as well as reinforce onboard medical autonomy of astronauts.

The Russian Institute for Biomedical Problems has deployed a sequence of software tools providing daily calculations of Baevsky's functional state algorithm terrestrially to assess wellness and adaption responses through the analysis of ECG to support knowledge discovery of the adaption process through longer and longer space missions by Russian cosmonauts over time. However, this architectural approach of retrospective calculation and the provision of a daily average score only are not a sustainable approach for future missions outside of low earth orbit (LEO).

The Knowledge Discovery component of the Artemis architecture supports in-depth temporal mining of incoming and stored data to down sample physiological data into temporal behaviors as an approach to identify new observable patterns that show correlation as condition pathophysiologies for various clinical conditions. This approach has been demonstrated in neonatal intensive care [24]. It utilizes McGregor's patented temporal mining approach discussed in detail in [24]. This approach presents great potential for missions to the Moon and Mars, as the astronauts will likely be subjected to new physiological conditions as a result of much longer exposure to conditions of spaceflight.

Space agencies and research institutions continuously explore and advance the methods utilized for knowledge discovery with the aim to make acquired data sets more manageable, accessible within a structured data warehouse, and to maintain its relevance to meet the healthcare objectives for human space missions.

8.11 Real-Time and Retrospective Visualization

Conventional data acquisition and processing approaches limited visualization of data to two-dimensional plots, hindering the ability of such visualizations to provide details about the dynamicity of temporal task-specific activity, as well as to depict trajectory of changes that occur in response to changing environmental, psychological, and physiological conditions [19]. The limiting factor of fragmented data collection and retrospective analytics still persists, impacting the ability to meaningfully utilize the biomedical data to inform decision making during spaceflight.

The Artemis platform presents an example of an innovative technological solution to support real-time analytics and a more interactive data visualization with minimal latency period between when the data is captured and visualized. Prior research has demonstrated a great potential of Artemis to support real-time spatio-temporal visualizations, aiding early detection monitoring, identifying the trajectory of health changes as the deviations from the norm become apparent Fig. 8.11, [19]. This approach further demonstrates great potential to support predictive analytics and discovery of early hallmarks of known and emerging pathological conditions associated with prolonged exposure to spaceflight environment.

8.12 Conclusion

As the human race pushes to personally explore space at greater distances from Earth, new approaches to assessing health, wellness, resilience, and adaption during space travel will be required retrospectively and prospectively. Innovative technological solutions will need to be developed to ensure compatibility of various biomedical monitoring modalities that can effectively contribute to an overarching autonomous medical decision support system to support prognostic, preventative, and therapeutic medical care aboard the spacecraft during deep space explorations.

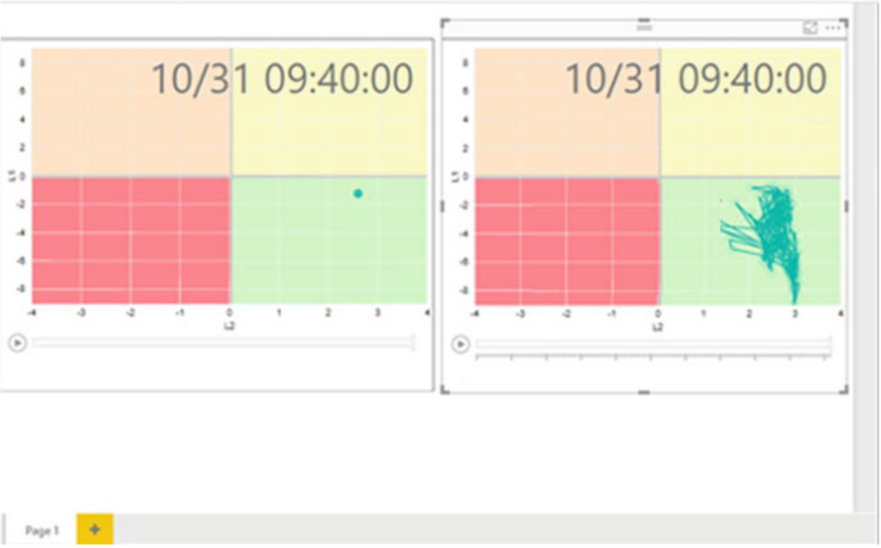


Fig. 8.11 In prior research Prysyazhnyuk and McGregor [19] proposed an extension to Artemis platform within the data presentation component to support dynamic visualization of physiological data streams in real-time, as well as for prospective clinical research. The proposed extension utilized Microsoft Power BI visualization product to enable mapping of health state changes, as well as identification of task-specific physiological responses, further enhancing the usability of functional health state algorithm during spaceflight

Communication delays, lack of ground-based input, and limited medical expertise of space crew are placing a great emphasis on human centered computing, which will leverage intelligent computer systems to advance human presence, all while preserving and maintaining health of its crew, in outer space habitats.

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Part IV
Earth

Chapter 9
Paramilitary and Military Tactical Operations as an Extreme Environment

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9.1 Paramilitary and Military Tactical Personnel Background

Many countries have established military-like forces that are not incorporated within regular armed forces. The jurisdiction of state sponsored paramilitary forces predominantly falls between the armed forces and regular police [28]. While the convergence of military and policing has occurred within many peace keeping international organizations and individual countries, terminologies for this type of organization are varied and include names such as special weapons and tactics (SWAT), paramilitary police, militarized police, and combined armies/police forces [5, 14, 28].

Scobell and Hammitt [28] note that the term paramilitary emerged over 80 years ago in 1936 when the term was used in London's White Paper on Germany to identify military style groups that had arisen in Weimar, Germany. However, the term was not defined in a systematic way, and they proposed the following in relation to the definition of paramilitary:

> A paramilitary force is a uniformed group, usually armed, neither purely military nor police like in format or function but often possessing significant characteristics of both.

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Paramilitary personnel are trained to deploy and operate as a unit rather than as individuals, have more specialized weaponry, more specialized apparel and equipment that regular police, and have ranking structures similar to those within the military [28].

Paramilitary personnel who are tactical police officers perform functions such as executing high-risk warrants, siege situations, and rescuing hostages. They can also be called to mental health crises and domestic disturbances [8, 14, 27]. They are highly trained personnel and face situations that present life-threatening events outside of the capabilities of front-line officers [19]. They are required to use some method of entry to breach and gain access and then search and methodically clear buildings, dwellings, commercial properties in order to exercise the warrant or rescue the hostage(s). They use special tactics, such as stealthy movements, like those used by military tactical personnel to force a suspect to move positions. During these activities they are often required to utilize and operate sub-machine guns, high-powered rifles, hand guns, grenades, gas-grenades, rocket propelled tear gas, stun guns, and guns that shoot bean bags [8, 14].

Other paramilitary personnel protect government and non-government assets such as transportation and utility assets. They are regulated by and overseen by the state but are independent to these government and non-government assets. For example, paramilitary personnel are used to protect nuclear power generation assets.

The working dynamic of paramilitary personnel is one of periods of inactivity with bursts of activity when they are deployed for a given operation. For their safety and to carry out their operations, paramilitary and military tactical personnel wear personnel protective equipment and carry a range of equipment. The remainder of this chapter introduces their activities and skills, the impact on the body of performing this work, the impact of their environment, the clothing and equipment that they wear and carry, the impact of biological sec and gender, training techniques and skills development, fitness development and load carriage conditioning, resilience development, and environmental acclimation.

9.2 Activities and Skills

To carry out their operations, paramilitary and military tactical personnel perform various activities utilizing a range of specialized skills. In the line of duty they are required to carry out several physically demanding athletic activities that put their bodies under physical stress such as [8]:

- Crawling.
- Jumping over, off, or across obstacles.
- Maintaining balance while traversing a narrow object or wall.
- Maintaining a tactical position for an extended period of time and remaining alert.

- Climbing fences, walls, elevator shafts, and multiple flights of stairs, ladders, fire escapes, ropes, poles, and trees to gain an objective or tactical position.
- Lifting and carrying necessary equipment—rams, breeching tools, ladders, shields over rough terrain (e.g., snow) across a reasonable distance (400 yards).
- Lifting and dragging wounded officers and citizens to safety in a reasonable time across a reasonable distance.
- Running to escape an area of danger or to cross an open area.
- Running to pursue a suspect or rescue a hostage.
- Functioning up on roof tops, ledges, and high positions.
- Functioning in crawl spaces, tunnels, vents, shafts, etc.
- Low and high crawling to objectives (100 yards).

In addition, they are required to perform several operation related skills such as:

- Utilizing breaching equipment to gain entry.
- Deploying pyrotechnics.
- Deploying a variety of ballistic, chemical, electrical weapons systems.
- Accurate weapon firing quickly while stationary and moving.
- Loading additional ammunition.
- Physically restraining an enemy combatant.
- Holding a ballistic riot shield.
- Rappelling from buildings or helicopters.

They are faced with several situations that place them under psychological stress due to [15, 20]:

- The risk of injury and death for themselves as a result of searching, clearing, maneuver, and engagement.
- An attack by the enemy combatant(s) on a forward operating base or patrol base perimeter.
- Indirect fire attack from incoming artillery, rocket, or mortar fire.
- Engaging enemy with direct fire or returning fire.
- A close call.
- Being shot or hit but their protective gear saved them.
- Becoming wounded in action.
- Seeing a team member wounded or killed.
- Seeing injured women, children, or men whom they are unable to help as they have to continue after the enemy combatant.
- Being responsible for the death of an enemy combatant.
- Being responsible for the death of a non-combatant.
- Exposure to human remains.
- Primary or secondary exposure to acts of violence.

In order to carry out the tasks required of paramilitary and military tactical personnel and to stay mentally healthy in the moment and over time, they must therefore carry out training activities to provide them with the physical fitness, skill development, and psychological resilience to demonstrate competency in all areas individually and collectively. Skill development training enables the generation of muscle memory.

9.3 Impact on the Human Body

Performing paramilitary or military tactical personnel operations has significant impact due to physical, psychological, and environmental stressors and demonstrates why tactical operations for both paramilitary and military personnel are considered an extreme environment.

9.3.1 Physiological Systems

When paramilitary and military tactical personnel respond, it causes an immediate impact on their physical and mental health and wellness. In addition, many situations are life threatening. These have immediate implications in the moment of any given operation for physical and mental injury as well as the potential for repeat exposure to lead to further chronic physical and mental injury. Physiological impact can continue well past the event in media and through social impact. The following subsections provide an overview of the impact on various systems within the body.

9.3.1.1 Musculoskeletal System

The impact on the musculoskeletal system for Special Tactics Operators within the US military was assessed and 24% of all lower-extremity injuries self-reported by Air Force Special Operations Command Special Tactics Operators were knee injuries [31]. A medical chart review in 2016 found that 14.5% of all injuries in which medical care was sought were located at the knee, the second highest sublocation only to shoulder injuries (20.9%). They concluded that the “high risk of injury to the knee in Special Tactics Operators could be related to the unique and significant physical demands of the occupation within challenging and austere environments (such as mountainous and urban terrain, as well as in swift-moving water and jungle environments) [31]. Specific skillsets used by Special Tactics Operators include ammunition load and carry, immediate action drills, moving casualties, building clearing, heavy weapon mounting and firing, rope techniques, water operations, and weapons proficiency, among many others” [9, 31].

9.3.1.2 Cardiovascular System

During an operation performed by paramilitary or military tactical personnel, the mental and physical stress on the body is intense. The sympathetic nervous system will increase activity as a direct response to the stress that they are under, and this will lead to a rise in heart rate during the operation. The extent of the rise and the ability to return to equilibrium during and after the operation will depend on their individual stress response and resilience. Further heart rate increases and elevation in respiration usually follow as the combat continues. Grossman et al. [13] performed extensive research on military personnel and the effects of fear-induced heart rate increase. They report that fine motor skill deterioration occurs with heart rates exceeding 115 beats per minute and complex motor skills deteriorate above 145 beats per minute. While there is a debate about the influence of cardiac fitness activity on these thresholds, they report a consistent milestone threshold across many domains, including motor racing, of 175 beats per minute. Beyond that threshold, a loss of depth perception, audio exclusion, and a loss of near vision can occur in addition to cognitive responses of freezing, fight or flight, and involuntary voiding of bladder and bowels. Such high heart rates also directly impact the heart's ability to perform its basic function of distributing nutrients and oxygen around the body and removing debris and carbon dioxide. Officers learn a tactical breathing technique in order to slow breathing and heart rate. This technique assists in physiological stress reaction reduction to help officers be in a physiological zone, the red zone [13], of 115–145 beats per minute for optimal performance.

9.3.1.3 Sensory Systems

The sensory system is part of the nervous system and provides the function of processing sensory input. The sensory systems are vision, hearing, touch, taste, smell, and balance. There are many ways that the sensory systems are impacted during paramilitary and military tactical operations (Table 9.1).

9.3.2 Psychological System

Paramilitary tactical personnel are activated when there are hostage and/or terrorist situations, active shooters, and other high-risk duties. As a result, they regularly encounter extremely stressful situations and incidents that are stressful in the moment and could have long lasting psychological impact. They face situations with life and death consequences for themselves, their team, innocent bystanders, and the perpetrators.

This results in significant psychological stress in the moment that can have immediate or longer term consequences.

Table 9.1 Sensory stimulus

Sensory system	Description
Vision	Vision during an operation can be impaired by environmental conditions such as smoke, mist, or fog or equipment such as goggles, helmets, and/or night vision goggles. It can also be impaired by structures being used to protect their bodies from the weapons of the enemy combatants. Vision can be impaired or damaged temporarily or permanently by debris. In addition to these external factors that can impact vision, Grossman et al. note that heart rates of over 175 beats per minute can cause: loss of peripheral vision (tunnel vision), loss of depth perception, and loss of near vision [13].
Hearing	The use of various weapons and pyrotechnics can lead to temporary auditory occlusion and or damage. In addition to these external factors. Extremely high heart rates as a result of stress response can lead to auditory exclusion [13].
Balance	Temporary damage to hearing can lead to temporary issues with balance. This is particularly relevant when an operation requires balance while traversing a narrow object or wall and stability while firing weapons.
Smell	Smells during an operation can impact paramilitary and military tactical personnel cognitively and psychologically. They can be exposed to the smell of smoke from weapons or smells relating to death and injuries. The use or presence of biological and chemical agents either deployed or environmental can occur also.
Touch	The kinetic effect of weapons firing can lead to a temporary impact on the sense of touch through the fingers, hands, and arms.

Tactical officers have a high prevalence of stress-related disorders, such as post-traumatic stress disorder (PTSD), anxiety disorders, depression, burnout, and substance abuse [2–4].

Regular and sometimes irregular judgment training is provided with result based performance training. These training scenarios are performed to evaluate if officers perform according to legalities within procedure and training. By repetition there is a reduction in the stress, but it is strictly performance and observation based.

Current training programs for tactical personnel do not incorporate techniques to maintain and improve autonomic nervous system control during deployment in highly stressful situations. That is, they do not enable approaches for paramilitary and military tactical personnel to develop resilience to the psychological stressors.

9.3.3 Environmental

Operations can take place in a multitude of environmental conditions that can affect both personal and equipment performance as well as the equipment and clothing required: from arctic cold to extreme heat, dry to torrential rain, and brightness of day to the darkest on nights. These environmental conditions can be fluid and ever changing during an operation.

If the paramilitary and military tactical personnel are not acclimatized to the environmental conditions such as an operation in the extreme heat or extreme cold, then their performance could be significantly impacted. Similarly, if their clothing is not appropriate for the prevailing conditions, their performance, motor skills, and cognitive performance could be hampered.

9.4 Clothing and Equipment

Paramilitary personnel predominantly wear uniforms to enable them to be identifiable with insignia of rank and organization. These uniforms are also considered part of their personal protective equipment for their personal protection. Functional consideration is given with respect to the practicality of colour and durability for the overall design and materials used for the uniforms. The colour and texture of the uniforms will usually reflect the need to camouflage in the environment. These functional considerations also include environmental factors of climatic issues relating to heat and cold as well as prolonged exposure to a range of weather and climatic conditions. Safety considerations of materials are required for flammability and melting. Clothing may also need to be reflective of the radiological, biological, and chemical conditions of the environment. Safety suits for exposure and protection against contaminants or contagions may also be required. Clothing needs to be given careful consideration for male and female body shapes and has a close relation and practicality to the considerations required for equipment they carry.

> Tactical officers are required to carry loads as part of their occupation. Carriage of these loads have been associated with causing physical injuries to the carrier and impairing their ability to perform occupational tasks. (Rob Marc Orr [23])

Similarly to the loads reported by Orr [24] for military personnel, paramilitary tactical officers are required to carry loads for their protection and to enable them to carry out the tasks they are required to perform. These loads can be for personal protection and equipment (e.g., weapon systems, body armour, gas masks, night vision devices, ballistic helmet, magazines, munitions, two or more weapons, asp, pepper spray, communications devices), sustainment (e.g., water), and task performance (e.g., breaching equipment, ballistic riot shield, additional ammunition). These loads are carried on the head (e.g., helmet, night vision devices), torso (e.g., body armour, additional ammunition), back (e.g., backpack, additional ammunition, pyrotechnics, additional protective gear, additional communications, and power-sources), hands (e.g., protective gloves, weapon systems), thigh (e.g., side arm, gas mask, other weapon systems, batons, restraints, illumination devices), or feet (e.g., boots). The combined weights of these loads for tactical officers can be approximately 20–50 kg, and they have to carry these loads during each shift and into unpredictable and hostile environments. They could be required to carry these loads for much longer during an active operation. Additional loads such as large ballistic shields (13.6 kg), battering rams (15.9 kg), and a range of forcible entry and prying tools (weight up to 10 kg each) may also be carried depending on the specific needs of the operation [14, 26].

Carrying these types of heavy load places stress on the Musculoskeletal system and Cardiovascular system of tactical officers and can lead to physical injury such as foot, ankle, knee and back pain, blisters together with stress fractures and neurological conditions like brachial plexus palsy and meralgia paraesthetica [24].

Orr [24] found in their review that load carriage impacts mobility and time taken to move including moving in and out of vehicles, which has the risk of increasing the tactical officer's exposure to hostile fire.

While reducing their load has great potential to reduce injuries, Orr found that loads of military tactical personnel are increasing [23, 24] and similar trends are happening for the paramilitary tactical personnel as well.

It is imperative as a result that any new load to be carried by tactical personnel for protection, tool, or stores be assessed in terms of its carry location on the body and the implications on the musculoskeletal system.

9.5 Impact of Biological Sex and Gender on Health and Wellness

Paramilitary and military tactical personnel have traditionally been predominantly males. As a result, research studies on paramilitary and military tactical personnel have been performed on all male or mostly male participant cohorts.

Elkins [10] performed a secondary use of data research study using a subset of 40 participants (100% male) consisting of ten teams of four military trainees who completed task training for building clearing. During building clearing, an armed team enters and moves through an entire building, and they must eliminate (shoot) all enemy combatant forces and identify and not shoot non-combatants in the building.

The assessment of fitness and conditioning training within tactical officers performed by Irving et al. [14] and Pryor [26] were performed on 130 and 11 male participants, respectively.

Davis [6] reported on the results of a self-reported survey completed by 86 participants. They note they gathered information on demographics such as sex but within the online survey tool[1] the question asked for gender and not sex. While they gathered this information the distribution of sex/gender was not reported in the paper. Dawes [8] assessed the physiological profiles of 71 male tactical officers and Pryor [26] performed as assessment of fitness characteristics on 11 male tactical officers.

Andersen [2] tested the feasibility of a resilience promoting training program designed for patrol officers with 18 male regional and federal special response team

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[1] https://links.lww.com/JSCR/A17.

(SRT) officers in Finland. In another study she examined the physiological arousal of seven metropolitan Canadian SWAT officers and 17 male SRT officers from Finland during training and real-work use of force incidents in order to determine what type of use of force training created similar physiological reactivity to that experienced during live police incidents. In addition, none of these studies specified whether this classification was based on biological sex or gender. The review of load carriage impact and condition by Orr [23] did not assess the impact or specific conditioning requirements by biological sex or gender. Historically, clothing and load carriage have been designed based on a unisex requirement and as such does not accommodate the fundamental differences in the male and female body structure.

As a result, it is unknown whether biological sex and gender needs to be considered in the assessment and development of skills, load carriage, fitness, conditioning, and resilience. Further research is required that stratifies results by biological sex and gender.

9.6 Training Techniques and Skill Development

Paramilitary and Military Tactical Personnel are required to develop a diverse range of skills. To achieve this goal they perform a diverse range of skill development training activities in simulated physical and virtual environments. It is imperative that training simulates real-world scenarios. Further details on skill development and training environments is provided in the following subsections.

9.6.1 Skill Development

Paramilitary and military tactical personnel train regularly to ensure that their skills such as precision weapon firing and situational assessment remain current. This is vital as without this regular training and practice, their skills are perishable [21].

Pryor et al. [26] describe four physical tasks performed by tactical operators, namely:

- Donning and use of tactical gear.
- Recon and securing of perimeter.
- Dynamic entry of structure.
- “Man down” drill.

The task list by Pryor is from the perspective of physical tasks to determine physical training. In addition to those physical skills, paramilitary and military tactical personnel need to develop skills for operational deployment in the areas of:

- Tactics

  - Building clearing (Dynamic/Stealth).
  - Containment.
  - Assaults/defensive.
  - Reconnaissance.

- Weapons systems both lethal and less lethal across multiple platforms for
  - Precision training.
  - Weapon maintenance.
- Legalities—knowledge and applications.
- Judgmental—proper use of weapons, tools, laws.
- Communications/negotiations skills/tactical communication.
- First Aid/Mental health skills.
- Pyrotechnics and explosives.
- Technical skills.
  - Technical breaching.
  - Specifics safety equipment and its use/maintenance.
  - Safety radiological/biological/chemical environments and equipment.
  - Rappelling/climbing.
  - Driving.
- Possible fitness training.

All these skills will have different testing and evaluation renewal periods dependent on department or federal standards.

Current training practices rely on repetition for skill development to build resilience and muscle memory; however, current training techniques do not measure physiological response during training as a means to assess the impact on the body and the degree of resilience.

9.6.2 Training in Physical Environments

A number of technologies are used during training to simulate real-world scenarios. Simunition (www.simunition.com) can be used for exercises at close range as it provides a realistic weapon that fires paint cartridges propelled by gun powder. Rounds striking targets provide an instant physical pain reaction and are visible as a result of the paint cartridge explosion on impact. While this approach enables trainees to use a realistic weapon and receive immediate tactile negative feedback, their use requires protective gear to prevent injury and spaces and structures for training need to be constructed [20].

An alternative to Simunition is Laser-marking systems. These systems enable weapons to have lasers mounted to them. Weapons are loaded with blanks and when they are fired, it activates laser pulses. Harnesses and halo sensors are worn by the trainees to detect the laser to indicate when the trainee has been struck by a laser.

Fig. 9.1 Tactical stack up before a building clearing scenario

These systems are widely used and are very popular in military training because the nature of the weapon enables them to be used in almost any environment. Hence this alternative provides more options of physical spaces for training than simunition. However, these systems provide no tactile response and thus have no realistic repercussions. The indication for being hit is audible indicators only.

There is significant overhead to enable physical training activities. Physical training environments require physical space and construction, undergo a strict safety protocol, and require trainees to wear safety equipment. Securing physical space for training and completing scene construction can be expensive. Training with excessive safety equipment can be cumbersome. Establishing safety protocols is often expensive and time consuming. Large-scale drills and exercises that involve integrated department responses using different systems are becoming yearly mandates in some areas. Real-world incidents are simulated by actors and special effects. However, creating these scenarios is expensive and requires significant planning and resources to execute these drills (Fig. 9.1).

9.6.3 Training in Virtual Environments

Virtual reality (VR) and immersive simulation environments (ISEs) are largely replacing physical training approaches. While VR and ISEs may have pitfalls in comparison to physical training approaches, the benefits of ease of repetition together with cost-effectiveness make this option a realistic alternative or compliment to physical training environments [20].

Many countries have begun to utilize virtual training approaches within their military tactical personnel training using software such as VBS3 from Bohemia Interactive Simulations (https://www.bisimulations.com/) that provide first person shooter training environments virtually. The same use within the paramilitary domain has not been as apparent. This could be due to the smaller size of paramilitary units as compared to military forces.

To date, these virtual training environments have focussed on the stimulation of visual and auditory senses only. Similarly to the laser system approach in physical training environments, this form of training lacks physical repercussions of being shot. In addition, auditory stimulation is usually not realistic from a directional perspective creating further misalignments with reality. When the training scenario does not adequately simulate the real-world equivalent, maladaptive plasticity can occur, as the training does not correctly match the real-world context.

Traditionally players interact with a virtual reality game through a keyboard or mouse. With the addition of a game controller, vibration sensations through the controller were introduced. In recent years, research to create haptic garments has occurred. To date none is available commercially. As Real As It Gets (ARAIG) is a multi-sensory immersive wearable technology designed by IFTech Inventing Future Technology Inc that enables tactile sensory cues to complement the visual and audio cues. McGregor et al. have demonstrated the potential of its use for skill development together with resilience assessment and development for paramilitary and military tactical personnel. They integrated ARIAG with the ArmA 3 first person shooter game from Boehemia Interactive Solutions and a Big Data analytics platform, Athena, proposed by McGregor to create resilience analytics [20]. ArmA 3 is a consumer smaller scale first person shooter game as compared to VBS3.

9.7 Fitness Development and Load Carriage Conditioning

Paramilitary and military tactical personnel need to maintain fitness. Tasks they are required to undertake often require sustained or repeated high intensity physical activity that will likely include physical conflict while carrying external loads [14, 26].

Irving [14] noted that fitness levels in the areas of muscular strength, power, aerobic capacity, and body composition of tactical police officers and non-tactical police offices have been previously found to be comparable with that of the general population. However, they conclude that this is inadequate given the increased physical nature of the occupation and the significant responsibility for community and personal safety dependence on the fitness levels of these officers. They note that no ideal aerobic capacity has been determined for tactical officers. They found that in general tactical officers were performing resistance training, aerobic activity, group exercise classes, extreme conditioning, occupational specific training, specific sports, and defensive tactics. Pryor [26] observed that trunk rotation, overhead upper extremity use, isometric upper extremity actions for firearm and shield use, explosive movements in formation, kneeling, and long waiting periods while wearing equipment were some of the frequent activities they performed. They concluded that to perform these job-related tasks, tactical officers required a blend of aerobic fitness, extremity strength, core strength, flexibility, and muscular power. However, they noted that the ideal fitness profile of high aerobic capacity, core strength, muscular power, and flexibility was not achieved by any single tactical officer of the 11 male participants within their study. They concluded that aerobic capacity, leg power, and flexibility should be the main focus to maintain their highest level of operation. To counteract the potential for injury, exercise specialists should focus on strength training of the core musculature while maintaining arm and leg strength.

The personal protective equipment and other equipment worn during tactical operations is burdensome, placing additional stress on the spinal column and core musculature. Individualized approaches to measure core strength and hip flexibility, together with a strength program addressing the core and extremities in a tri-plane fashion, is required as a supplement to typical multi-joint resistance training, to prevent occupational back injuries [26].

As noted previously, tactical officers are required to carry a load that can impact their musculoskeletal system. Orr [23] concludes that, “for the tactical operator, conditioning to increase and maintain load carriage resilience forms an essential risk management strategy through which the negative impacts of load carriage can be managed and essentially reduced.” They propose that this conditioning must consider frequency, intensity, time, and type of load conditioning to increase effectiveness. However, Irving [14] notes that while tactical officers should carry out load carriage specific conditioning, the frequency and duration for which they carry their loads and in particular while engaged in the high intensity tasks they are required to perform, their specific training needs may be met by these operational activities.

A key challenge to date is assessing whether the fitness and conditioning programs for tactical officers are sufficient. There is a lack of research relating to fitness profile requirements for tactical officers [8] and there is a lack of research that aligns specific tactical officer tasks with fitness and conditioning [14]. In addition, to date there is a lack of research on the creation of methods, tools, and techniques for personalized fitness and conditioning programs that enable the tactical operators to assess and develop their own personal fitness and conditioning as it relates to their own load carriage and tasks.

9.8 Resilience Assessment and Development

Resilience refers to one's ability to bounce back from physical or mental adversity or effectively adapting in the face of adversity, stress, or trauma (American Psychological Association). It is differentiated from other related psychological concepts such as hardiness, which is considered a personality trait, in that it is believed to have both trait and process components [11]. This means that resilience is more dynamic in nature—it is expected to vary across time and individuals—and therefore is more amenable to assessment, intervention, and development. Davydov et al. [7] note that while resilience is an important component of mental health, resilience as a concept has been criticized due to definition ambiguities and challenges relating the stress someone has to experience and have an acceptance level of response to be termed "resilient." Similarly to the challenge of relevant physiological thresholds for qualifying physically to be operationally ready, there is uncertainty for the competencies that an individual is required to demonstrate in order to be qualified as resilient for any given stressors.

As previously noted, the nature of paramilitary and military tactical personnel operations results in periods of inactivity with bursts of activity. A key component of resilience for police is the ability to have in-the-moment responses, noting that "resilience is both psychological and physiological flexibility in the face of adversity" [1]. They highlight that Masten [18] notes that what is required in the moment is a conscious awareness to enable the determination of the best course of action, together with the best time to take action. Paramilitary and military tactical personnel are faced with situations where in the moment responses are required and management of personal physiological response is of paramount importance. The key in this context then is control over physiological stress responses and the ability to recover from those exposures [18]. Without such control, their body continues to live in a state similar to fight or flight producing cognitive impairments and leads us to feel pressured and on edge.

Resilience training programs are based on the premise that reducing psychophysiological reactivity (i.e., cardiovascular and respiratory parameters) during stressful incidents improves health and performance outcomes.

General stress resilience may be a practical and detectable metric, with higher levels of resilience serving as protective factors for PTSD and other psychopathologies [29]; nevertheless many questions remain regarding characteristics of successful technological interventions in mental resilience training including: (1) what are structured design approaches for resilience interventions; (2) what technologies are effective; and (3) what measurements can be used to assess resilience. Vakili and colleagues conclude by recommending an intensive interdisciplinary study of potential technological approaches that account for individual histories and specific experiences. Accordingly, new approaches for personalized resilience training analyzing individual physiological responses utilizing Big Data analytics techniques appear well-warranted for correlating and analyzing training data together in conjunction with their physiological responses.

Therefore, a systemic approach has great potential to not only impact job performance, but has significant psychological implications by providing techniques to enable personalized assessment and development of resilience based on physiologic response. In addition, providing an approach that enables the assessment of response to elements within an overall activity will help participants and the training team understand what elements are stressful for each individual.

A psychoeducation focused resilience promotion training program that was developed for police stress and resilience was applied to SWAT officers [2]. The program utilized audio recordings to immerse participants in reenactment of scenarios and proposed breathing techniques and imagery for resilience promotion techniques. They measured resilience development through the longitudinal assessment of heart rate and breathing during repeat exposure as a means to measure the development of resilience.

Recent research is utilizing formalized stressors in a structured way in resilience training as detailed by Johnston et al. [15] and Ogden et al. [22]. The stressors and triggers that these researchers identified in mission tasks were [15]:

> ... involving searching, clearing, maneuver and engagement that increase risk of injury and death, including: clearing or searching homes or buildings, indirect fire attack from incoming artillery, rocket, or mortar fire, attack by enemy on forward operating base or patrol base perimeter, and engaging enemy with direct fire or returning fire, a close call, was shot or hit, but protective gear saved you; wounded in action, seeing ill or injured women or children whom you were unable to help, being responsible for the death of a non-combatant/enemy combatant, and exposure to human remains.

9.9 Environmental Acclimation Training

Paramilitary and military tactical personnel will likely face different climatic conditions during deployment operations including conditions of extreme cold or heat and humid or dry environments. In addition to the physiological response to combat, individual coping mechanisms for climatic stress lead to varying individual stress responses. Each individual will have different degrees of exposure to these extreme environments based on life experiences that enabled them to build their own individual resilience to some climates. As a result, training activities should include personalized environment acclimation training for the environment(s) within which the paramilitary and military tactical personnel will be deployed.

Early acclimation research in human subjects dates back to the late 1950s [16]. Although studies have been performed on acclimation in extreme heat and extreme cold, the focus has been on post analysis of data for population based studies [12, 16, 17, 30], rather than the creation of personalized acclimation assessments proposed in this proposed solution.

Malgoyre et al. [17] note that full acclimation for military personnel can be achieved after 15 days; however, research in acclimation for athletes and public safety personnel wearing personnel protective equipment (PPE) have reported 5–

6 days of repeated exposure creates the most incremental adaption response after which, the degree of incremental change diminishes significantly [16]. In addition, studies have reported different adaption behaviours when the exposure is close sequence exposure verses more distant longitudinal exposure.

They further note that pre-deployment acclimation activities that include fitness training reduce perceived thermal discomfort during deployment. In addition, Yamazaki [30] note that fitness training in heat acclimation should be performed without PPE. This is because of the impact of excessive sweating on their uniforms, which alters the acclimation experience.

9.10 Relationship with Exposure Therapy for the Treatment of PTSD

PTSD treatments are increasingly incorporating information technology [25]; however, progress in utilizing information technology tools within training programs designed to strengthen mental resilience before potentially traumatic event exposures is nascent. There is great potential for using computing techniques such as Big Data and artificial intelligence, physiological interaction, and biofeedback to provide stimuli for measuring and developing resilience in ways otherwise unavailable for therapists.

9.11 Implications and Applications for Other Public Safety Personnel

In this chapter we have provided an overview of the domain of paramilitary and military tactical operations. The types of activities they are required to carry out and the skills they need to develop for these activities within various operations were introduced to demonstrate how tactical operations is a form of extreme environment. We outlined the personal protective equipment they wear and the range of equipment they carry regularly or for specific operations to provide context for their load carriage and the injuries they are at risk of to the back, knees, ankles, and hips as well as the threat of injury during an operation or death. Understanding what they have to wear and carry is important in any design of clothing or other equipment they may be asked to wear for monitoring their physiology, their musculoskeletal behavior, location or other technological needs. The differing conditions they operate in and their acclimation to those settings can impact their performance and also impact the equipment they are carrying.

Paramilitary and military tactical officers are predominantly male. Biological sex and gender implications are under-explored in paramilitary and military tactical officers as studies to date have been performed on all male participants or do not report on the biological sex or gender of the participants. As a result, there is great potential to perform further research that stratifies results by biological sex and gender.

Real-world and virtual training techniques both have challenges and opportunities; increased used of virtual reality training requires appropriate sensory feedback to ensure the realism of the training activity. Similar issues relating to load carriage, acclimation, resilience development, and the opportunity of virtual reality training exist with other public safety personnel who are required to wear body armour such as border security officers as well as firefighters.

There are significant opportunities to provide new approaches for personalized assessment and development of skills, resilience, fitness, load carriage, conditioning, and acclimation. In the next chapter we outline opportunities and challenges for engineering, computing, and information technology solutions for use with paramilitary and military tactical personnel.

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Chapter 10
Engineering and Information Technology for Paramilitary and Military Tactical Personnel

Carolyn McGregor AM and Brendan Bonnis

10.1 Background

Military tactical personnel are deployed to perform various military operations during times of conflict and operations other than combat such as peacekeeping, aid to civil powers, policing, humanitarian aid missions, disaster relief, supporting international training and development goals. Paramilitary personnel can be tactical police officers who execute high-risk warrants, resolve barricaded subjects, armed persons and hostage rescue. Other paramilitary personnel protect government and non-government assets such as transportation and utility assets [1]. Paramilitary personnel operate within a uniformed group, are usually armed and often possess characteristics of both military and police [2]. An overview of the paramilitary and military tactical personnel that includes details of activities and skills, the impact on their bodies, clothing and equipment together with training techniques and skill development is found in [1].

Paramilitary and military tactical operations are a complex man–instrumentation–equipment–environment ecosystem. The skill competency, health, wellness, resilience and adaptation of each of the deployed paramilitary or military tactical personnel can have important implications for the success and risk of failure of any operation. Assessing and improving the skill competency, health and wellness of each paramilitary and military tactical member along with their degree of resilience

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to stressors and adaptation for operational tasks and environments have great potential to improve the probability of mission success. To enable this, standardized approaches are required to collect, acquire, transmit, integrate, analyse, store and visualize data about the individual. Contextual information such as activity, stressor and environmental data enables a more wholistic assessment.

Paramilitary and military tactical officer skills and resilience are developed over time. They are also perishable if not repeated through regular training activities. This repetition enables an assessment of changes over time of an individual's development and improvement.

While paramilitary forces emerged over 80 years ago [2], the focus on assessing the impact on physiology and psychology has not progressed in the same way as it has in other extreme environment domains such as space. The recognition that this profession could impact physiology and psychology in the short or long term was not recognized for decades. Only after research demonstrated higher than general population incidences of cardiac issues, mental health issues and injuries to shoulders, back, knee and ankles, has there been a recognition that understanding the impact on these officers needs to be further investigated.

Several military forces have proposed concepts of a 'future soldier' since the turn of the millennium, and however, a lack of documentation due to security restrictions has limited unclassified dissemination of activities in this area. Yet, there are details that provide evidence that this form of monitoring of paramilitary and military personnel is in its infancy. The use of information technology hardware and software in paramilitary and military tactical operations has focused on the functions of gathering and sharing data related to the operation and for communication and control of paramilitary/military assets. As a result, the focus has been on surveillance, intelligence gathering, command, control and communications [3].

Engineering and information technology solutions for skill development together with improving the health, wellness, resilience and adaptation of paramilitary and military tactical personnel are required for both live operations and training activities. Training activities can be within simulations which have historically been focused on the creation of real-world scenarios [4]. However, these scenarios can be in virtual reality or on the spectrum in between physical and virtual within the domain of augmented reality. There are different requirements, particularly in the area of security, based on whether they are participating in a training exercise or live deployment, and this impacts engineering and information technology solutions within these domains.

Given the infancy of information technology and engineering solutions in this domain, this chapter outlines types of data that are important to collect from paramilitary and military tactical personnel during live and training operations. It then outlines requirements to collect, acquire, transmit, integrate, analyse, store and visualize data about the individual together with other contextual data to enable assessment of skill competency, health, wellness, resilience and adaptation.

The chapter structure follows the systemic information systems approach to the creation of analytics platforms for paramilitary and military tactical personnel as detailed in [22], which have then been described as they related to all extreme environments within Chap. 2 of this book.

10.2 Paramilitary and Military Personnel Data

In order to provide individualized and population-based assessment of the health, wellness, resilience and adaptation of paramilitary and military tactical personnel, data needs to be collected, acquired, transmitted, analysed, visualized and stored. This data can provide detail in relation to their physiological, psychological and cognitive state together with other personal data. This should be given context based on the activity or task they are performing, their load carriage, their environment and any medication or drugs that could impact the ability to perform the activity or task. Each of these forms of data is discussed within the remainder of this section.

10.2.1 Physiological Data

The physiological demands on their bodies impact the musculoskeletal, cardiovascular and sensory systems, and as a result, data that provides detail in relation to these systems is required, as noted in the previous chapter introducing the domain of paramilitary and military tactical personnel.

From a musculoskeletal perspective, the ability to assess the movement and strain on muscles and the skeleton is required in order to prevent injury through the use of inappropriate techniques and muscle development deficiencies. As noted in the previous chapter, due to the frequency of injury, the measurement of the impact on knees, back, shoulders and ankles is required.

From a cardiovascular perspective, it is important to understand the behaviour of the heart, the blood vessels, the ability of this system to provide nutrients and oxygen throughout the body and the ability to remove waste and carbon dioxide from the body. Failure of the cardiovascular system can lead to medical situations such as developing physical tunnel vision or more significant health conditions such as loss of consciousness.

Heart function assessment to date has focused on the analysis of the electrocardiogram (ECG) and the derived heart rate. In addition to provisioning data for the ECG, the three-lead ECG electrode configuration across the chest enables the analysis of chest wall movement through the analysis of the ECG electrode impedance, which is then analysed to determine breathing patterns and respiration rates [8].

Assessing blood pressure is also important. However, continuous measurement of blood pressure is not practical during tactical training and live operations. As a result, pre and post blood pressure or regularly scheduled blood pressure measurements are more practical options for acquiring this form of data.

The delivery of oxygen throughout the body can be measured using non-invasive blood oxygen saturation monitoring; however, movement artefact can impact the quality of this signal. In addition, locating sensors on hands to measure this is not practical, and locating them on the ear can impact communication earpiece equipment.

The measurement sweat levels can provide other information about how the individual is responding to their situation and environment. The measurement of cortisol from fluids such as saliva, urine and sweat provides details of how the body is responding to stress.

From a sensory system perspective, information about sensory stimulation during the training scenario provides important contextual information. As a result, collection of information relating to how vision, hearing, smell and touch are being stimulated during the training scenario provides key contextual information on the sensory stressors that are occurring during training scenarios.

10.2.2 Psychological Data

Paramilitary and military tactical personnel are placed under psychological stress during tactical operations [1]. Physiological responses for "in the moment" reactions as well as longitudinally are important to assess psychological wellness and resilience. Physiological data has been shown to enable the assessment of stress response as a measurement of the reaction of the nervous system. This nervous system response can assess immediate reaction in the moment for resilience assessment as well as post activity to assess the ability to return to equilibrium known as homoeostasis. Physiological data, such as cardiovascular data, can be used as an assessment of wellness longitudinally to determine long-term chronic deviations from homoeostasis. These chronic deviations from homoeostasis can be forms of posttraumatic stress disorder that result from individual or a group of traumatic stress injuries [9].

In addition to the analysis of physiological data, psychological checklists are used to assess perceived psychological state. These checklists support self-assessment and reflection. The integration of psychological checklists enables the progression of research on associations between psychological behaviours associated with various job-related activities and stressors.

10.2.3 Cognitive Data

Capturing data in relation to assessing the paramilitary and military tactical personnel's ability to observe and recognize threats/cues, which are both behavioural and situational, while responding appropriately is important to assess the cognitive skill and capacity of the tactical operator during live operations and training activities.

As a result, it is important to capture information about decisions they make and actions they take as a direct result of the behavioural and situational analysis.

10.2.4 Other Personal Data

To provide a comprehensive view of paramilitary and military tactical personnel, other personal data should be collected such as demographic data, medication and drugs and broad health and sleep data.

10.2.4.1 Demographic Data

Demographic data about the participant provides additional contextual information that could influence performance. Biological sex, gender, age, height, weight, race, ethnicity, family and carer responsibilities and disabilities are just a few examples of demographical data used to create a more contextually rich picture of individual paramilitary and military tactical personnel. There are fundamental differences between the biological sexes within the musculoskeletal system. Biological sex, height and weight can impact the load carriage behaviours. Gender and carer responsibilities may lead to different baseline resilience levels. As a result, the impact of demographics on health, wellness, resilience and adaptation in this population should be explored further.

10.2.4.2 Medication and Drugs

Drugs are defined as both ‘a substance used as a medication or in the preparation of medication’ and more broadly as ‘a substance other than food intended to affect the structure or function of the body’.[1] These substances create a pharmacokinetic (PK) response that reflects the movement of the drug within the body and a pharmacodynamics (PD) response that represents the biological response at the effect site(s) within the body. As a result, the ingesting of coffee and other caffeinated beverages and foods, together with cough, cold and other prescribed medication can cause an impact on the body. Medication and drugs can impact the performance of paramilitary and military personnel, and hence, the collection of information about medication and drugs is important for context.

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[1] (https://www.merriam-webster.com/dictionary/drug).

10.2.4.3 Broad Health and Sleep Data

Information relating to broad assessments of health, fitness and sleep all provides further important contextual information. Lack of sleep and reduced sleep can impact cognitive function and create a stressor on the individual.

10.2.4.4 Load Carriage Data

Paramilitary and military tactical personnel are required to carry a significant load. The amount of load carriage for paramilitary and military tactical personnel can vary from person to person as well as day to day. Operational requirements, environment and individual needs can broadly affect the load requirement. Gathering information about each individual's load carriage provides important contextual information with respect to in the moment impact of the load carriages as well as supporting longitudinal assessment.

10.2.5 Scenario Data

Paramilitary and military tactical personnel perform a diverse range of skill development training activities in simulated physical and virtual environments. It is important to collect information during the training scenario such as the activity they are performing, the stressors along with environmental data. This form of data could be collected from live operations as well.

10.2.5.1 Activity Data

Activity data provides much needed contextual information to be utilized when assessing physiological and psychological response. The specifics of the operation may vary from a static well-resourced operation to an extended dynamic operation. Operators may be required to run, crawl, climb, drag, shoot and/or physically restrain. They may be standing or prone for extended periods.

Information about the activities performed can be text or code based. Online entry systems enable immediate integration of activity data with other data from the operation or training activity. Visual recordings provide a means to cross reference with other forms of activity data collection. This is particularly important in the absence of a controlled environment where gathering of activity data in other ways may be difficult.

10.2.5.2 Stressor Data

Paramilitary and military tactical personnel are exposed to a range of stressors that can have varying degrees of impact on the individual based on the degree of resilience they have developed to that stressor. The Walter Reid Army Institute for Research developed a set of formalized stressors and triggers in mission tasks that can be used as encodings for data collection during training and live activities including 'searching, clearing, maneuver and engagement that increase risk of injury and death, including: clearing or searching homes or buildings, indirect fire attack from incoming artillery, rocket, or mortar fire, attack by enemy on forward operating base or patrol base perimeter, and engaging enemy with direct fire or returning fire, a close call, was shot or hit, but protective gear saved you; wounded in action, seeing ill or injured women or children whom you were unable to help, being responsible for the death of a non-combatant/enemy combatant, and exposure to human remains' [5]. This provides a standardized approach to resilience definition enabling individualized skill assessment across a range of stressors.

10.2.5.3 Environmental Data

Environmental data, such as the temperature, humidity, wind speed, the presence and degree of fog or smoke together with degree of light, can all impact the ability of the paramilitary and military tactical personnel to complete their activities. As a result, gathering environmental information provides valuable contextual information.

10.2.5.4 Position Information

While position information for a firefighter, for example, can be lifesaving, position information for a paramilitary or military tactical personnel can be life-threatening. As a result, position information could be used during a training activity but has security implications in a live deployment.

Position information in the real-world setting can be provided through GPS tracking. Exact positioning may not be possible. Triangulation from sensors worn by individuals can provide position information.

Within a virtual reality training context, the details of exact positioning within the game are possible.

10.3 Data Collection

Data collection enables the collection of various forms of data from paramilitary and military tactical personnel, the operation and environment before or during live and training operations.

Internet of Things (IoT) technology is being used for training and simulation as well as live operations involving tactical personnel. Live training scenarios, such as ‘shoot houses’, use cameras, motion sensors and acoustic sensors to track tactical personnel. In some cases, live feeds of this data are available to enable trainers to provide feedback based on physiological data to trainees in real time [3]. However, video editing and basic statistics derived from these approaches often require manual annotation of video which can be quite labour-intensive. These sensors do not provide information relating to an individual’s physiological and psychological response. Cognitive response can be assessed to some degree from the assessment of their behaviour during the operation.

Collecting data from the individual and environment can present many challenges due to the extreme environment, movement, protective clothing, equipment they are using or carrying and the tasks they are performing. Monitoring equipment will need to be incorporated in an already limited real estate of an operator’s equipment. In addition, the saying ‘train as you fight’ is very specific in the desire and effectiveness of having equipment as well as environment replicate as close to real operational conditions as possible. This is extremely relevant when considering any data collection equipment that is worn and/or carried.

Consideration of sensor placement is important within this context. Care needs to be taken for any sensors that are placed on the hands to ensure they do not impact the individual’s abilities to use their hands. The use of earpieces for communication can impact the use of the ear, for example, as a location to measure blood oxygen saturation. The use of haptic garments can interfere with the signal from these sensors and vice versa.

10.3.1 Physiological Data Collection

10.3.1.1 Cardiovascular Data

An electrocardiogram (ECG) is commonly used to detect the heart function. A three-lead ECG configuration enables the creation of an ECG waveform that detects the electrical and valve behaviour of the heart. One primary metric derived from the ECG is the primary beat annotated as the R peak in the ECG. The distance between successive R peaks is used to derive a heart rate and to assess heart rate variability.

In addition, assessment of the resistance between the three electrodes on the chest that measure ECG of the participant enables the creation of a waveform that provides information about the movement of the chest wall during breathing. From this breathing pattern, respiratory rate and respiration behaviour information can be derived.

Plethysmography can be used to provide information about the oxygenation of the blood and also provide pulse wave for the derivation of pulse rate. Enabling two forms of calculation of the heart rate is an important form of data collection redundancy creating two sources for the same measure. Cortisol and sweat measurement are also methods of assessing physiological response.

Physiological data has been collected from tactical personnel within a few published research studies. The Zephyr BioHarness has been used to collect electrocardiogram data from tactical officers during research studies involving tactical personnel in Finland and Canada. It has been used to collect physiological data from a group of all male tactical officers who were seated listening to critical incident scenarios on iPod devices [6]. Heart rate was analysed retrospectively as part of a population-based study to examine the effectiveness of a method of breathing on tactical personnel resilience. In addition, pulse oximetry was collected via an earlobe clip using the Inner Balance app and analysed retrospectively. A Zephyr BioHarness was worn by 24 male tactical officers in Canada and Finland during training and active duty hours. Statistical population-based analysis of the heart rate was performed retrospectively [7].

We have used the Zephyr BioHarness to demonstrate a new approach to assess personalized resilience and acclimation physiology in our extreme climate acclimation research where we created a 6 h deployment scenario for tactical personnel in an interconnected set of climatic chambers set to 50°C [8]. In that work, data was collected and transmitted in real time to the Zephyr control station software and then forwarded to the Athena platform, a big data AI-based computing platform, where it was integrated with activity and environmental data for personalized resilience and adaptation assessment.

10.3.1.2 Sensory Data Collection

Capturing information relating to the sensory stimulation that is occurring during the training scenario or live operation provides important contextual information. Methods for capturing this form of information from real-world scenarios are different from those available when using virtual reality or augmented reality scenarios.

Within real-world training scenarios, different forms of simulated weapons can be used. Simunition[2] enables the use of a realistic weapons to fire paint cartridges propelled by gun powder. Rounds striking targets provide an instant physical pain reaction, and the location is indicated with paint. This system requires protective gear to prevent injury and a strict safety protocol [11].

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[2] www.simunition.com.

During virtual reality or augmented reality tactical training, enabling the participant to feel the response to weapon firing, being injured and touch-based communication increases realism. Haptic garments have great potential to increase the realism of virtual reality training simulations. As Real As It Gets (ARAIG) is a multi-sensory immersive wearable technology designed by IFTech Inventing Future Technology Inc that enables tactile sensory cues to complement the visual and audio cues. The output from the virtual reality training scenario game that is used to stimulate the ARAIG garment can be captured to gather information about the touch stimulation that is being generated within the virtual reality training scenario game [12]. This form of haptic garment can also be integrated for use with Simunition systems such as Multiple Integrated Laser Engagement Systems (MILES).

Eye tracking software can be used to assess visual response to queues and stressors while using virtual reality to assess where the participant is looking. Ideally, the eye tracking software will provide coordinates in the two-dimensional x and y plane with a timestamp for each participant to provision a stream of data outlining where they are looking at any given point in time through the training exercise.

The introduction of various smells within the training context can lead to stress responses in trainees such as the smell of gun powder and burning flesh. These scents can be introduced strategically in real-world, virtual reality and augmented reality training simulations in a controlled way throughout the training activity. Activity-based logging can be used to track when they are introduced to enable the trainee responses to the stressors of having a given smell introduced.

Event-based logging can assess auditory stimulation from gun fire, pyrotechnics or screaming. Annotation of video feeds from the training scenario can provide this event-based annotation from real-world scenarios. Game outputs can be created to provide automated annotations of auditory stimulation and stressors for virtual and augmented reality training scenarios.

10.3.2 Psychological Data Collection

Psychological responses for in the moment reactions as well as longitudinally can be assessed through either physiological response or self-reflection using surveys and checklists. Physiological responses such as the measurement of sudden increases in heart rate provide a quantitative measure of the nervous system response.

Participant self-reflection can be measured using standard questionnaires. These questionnaires can be administered online to enable easy integration of their responses within an integrated platform.

Inverse associations between heart rate variability and posttraumatic stress disorder (PTSD) scoring were found through a pilot study of veterans using the Clinician Administered PTSD Scale (CAPS) and PTSD Checklist (PCL-S) [9]. In a broader coronary heart disease population, heart rate and heart rate variability changes were associated with changes in the degree of depression as measured using the National Institute of Mental Health Diagnostic Interview Schedule [10]. Thus, heart rate variability has the potential to detect the presence of mental illness broadly.

10.3.3 Cognitive Data Collection

The tools available to capture cognitive performance can be different between the real-world and virtual/augmented scenarios.

As noted in the earlier section, outlining the types of data that are required to be collected, it is important to capture information about decision-making and actions taken as a direct result of the behavioural and situational analysis. The ability to observe and recognize threats and delineate from non-combatants can be assessed within the virtual/augmented context through capture of weapon use data within the virtual/augmented environment.

Similarly, to sensory stimulation data, in real-world live and training scenarios, event-based logging can be manually introduced to record actions, choices and events.

10.3.4 Other Personal Data

10.3.4.1 Demographic Data Collection

As noted previously, it is important to collect demographic information from paramilitary and military personnel for additional contextual information. Information such as biological sex, gender, height, date of birth, race and ethnicity, for example, could be collected initially and collection of weight and carer responsibilities and disabilities are examples of demographics that can change over time. Online collection through data entry enables direct entry into an online storage environment and the provision of this information can be performed by the participant in their own time.

10.3.4.2 Medication, Drugs, Health Status and Sleep Patterns

Similarly, to demographical information, information about medication, drugs, overall health status and sleep patterns is important contextual information and can be collected via online forms completed by participants in their own time.

10.3.4.3 Load Carriage Data Collection

The amount of load carriage for paramilitary and military tactical personnel is significant. Due to the heavy load of primary equipment, any additional data collection equipment will have a cumulative taxing effect. Positioning of the equipment could also have impact on the musculoskeletal system.

During virtual reality simulations, if the trainee is seated playing the video game, load carriage, whether worn or not, is not simulating reality. However, if the trainees are able to stand, squat or lay down during the augmented or virtual training, then provision of the appropriate load carriage will increase realism. Load carriage and trainee positioning during training should be recorded in virtual reality and augmented reality training.

While load carriage information can be collected using a traditional forms-based approach, visualization tools can be used to enable drag and drop assembly of load carriage information by placing load within the three-dimensional space from a virtual list of load carriage component options.

10.3.5 Scenario Data

10.3.5.1 Activity Data Collection

As noted in the prior section outlining the types of data, activity data provides much needed contextual information. Methods that can be used to collect information about the activities and tasks that the paramilitary and military tactical personnel are performing vary depending on whether it is a live or training operation. Within the context of training, it can vary depending on whether the operation is a real-world simulation, virtual reality or augmented reality.

Within a live operation, collection of activity data can be challenging given the live and dynamic setting. Video cameras mounted on the tactical personnel are one method to enable video capture. However, these videos need to be annotated usually through retrospective review which can be time-consuming. Some degrees of automation of this step can be achieved through pattern recognition from the video for certain forms of activities.

Similarly, for real-world training simulations, video cameras mounted on the tactical personnel can be worn along with fixed position video cameras within the theatre of operation. Training assistants can manually annotate activities during the training operation using video feeds as camera locations can be well planned in advance to ensure placement will enable capture of the different elements within the activity that are required [8]. Simunition fires paint cartridges propelled by gun powder. Data collection of whether they were hit can be performed post exercise through inspection for paint, however, the details for when they were firing, and fired upon, are not available in a similar way. Review of video, if available, can provide this information.

A second form of weapons system that is used within these real-world training scenarios is the Multiple Integrated Laser Engagement System (MILES). Weapons are mounted with and the firing of blanks activates laser pulses. Harnesses and halo sensors worn by trainees indicate when struck by a laser. This laser tag type of system can be used in almost any environment [3, 11]. This form of weapons system has the potential to collect information about who is firing upon whom, at what time, and what location was hit.

Virtual training environments, whether virtual or augmented reality, enable more opportunities to gather activity data. Location, time, weapons used, location of hits on the combatants and non-combatants are all examples of data that are used by the game that could be collected. In addition, activities such as shoulder squeezes for communications, door breach tasks and use of pyrotechnics could also be tracked. In prior work, we demonstrated how this type of data could be collected from the first person shooter game ArmA 3 [12].

Within the training context, a structured approach to activity design such as that proposed in [13] enables learning outcome-based goal-oriented design of activities. Activity timing data together with other contextual data, such as the number of combatant and non-combatant targets hit, can be carefully planned to support individual assessment of performance and skill development over time. A consolidated list of the types of activities performed by paramilitary and military tactical personnel can be found in detail in the previous chapter.

10.3.5.2 Stressors Data Collection

To enable the effective development of resilience within paramilitary and military tactical personnel, providing a mechanism to collect information about stressors is vital.

We have proposed a structured approach to scenario design that was demonstrated within the context of virtual reality game simulation design [12]. Through this approach, the scenarios can be created with the goal of assessing a given set of skills and stressors and these skills and stressors are mapped to game function. A similar approach could be used to map the stressors to their manifestation within a real-world scenario. This data can then be integrated with other data from the scenario to create an integrated picture. During real-world simulations, manual annotations using online forms during the training scenario or retrospectively using video of the training scenario will provide details of the timing of the stressors introduced. Stressors provided in augmented or virtual reality-based training can be automatically annotated via event-based outputs from the video game that can be programmed in advance. We demonstrated this principle in [14] through the creation of Mods within the first person shooter game ArmA 3.

10.3.5.3 Environmental Data Collection

A range of environmental sensors can be used to enable the collection of environmental information from live and real-world training scenarios such as the temperature, humidity, wind speed, the presence and degree of fog or smoke together with degree of light. This information is also relevant in augmented reality training scenarios.

In addition, room temperature and humidity levels should be noted for virtual reality training simulations and indoor augmented reality simulations as these forms of training scenarios can be performed in climatic chambers to introduce heat stress. The amount of light and presence of smoke/fog in the virtual or augmented reality training scenario is relevant to collect also to assess the degree of visibility within the virtual reality environment.

We have demonstrated an approach to collect temperature, humidity and wind speed from an integrated set of climatic chambers within the Ontario Tech University's ACE Facility as part of an approach to pre-deployment acclimation assessment and development for extreme climates for military and paramilitary tactical personnel [8].

10.3.5.4 Position Information Collection

GPS tracking tools can be used in training scenarios to provide position information, but their use during live scenarios requires appropriate security consideration. Similarly, triangulation of signal strength from worn sensors can provide position information as well.

10.3.6 Data Quality

The quality of data collected from sensors is paramount to ensure that the data reflects the actual reality. Artefacts represent erroneous data which can be caused by many factors. Some artefacts such as complete signal loss can be easily detected, whereas other artefacts are subtler and more difficult to detect that the sensor is not recording reality.

Within the context of paramilitary and military tactical personnel, there are specific potential sources for artefact within signals from sensor data. Tactical officers can move very swiftly when deployed and may be involved in physical contact to apprehend. They use a range of weapons whose ballistic properties can cause signal interruption. As a result, any sensor equipment should be tested within these contexts to assess the presence and degree of artefact that occurs as a result of those situations and equipment. Some additional factors to consider are detailed below.

Water Tactical officers may be required to enter water in the line of their duties. As such, data acquisition approaches need to be able to work in the water and/or be waterproof.

Redundancy A data acquisition design for tactical officers needs to consider what degree of redundancy is required. That is, what degree of duplication of sensors should exist to ensure continuous data collection. In addition, should the redundancy be based on parallel or sequential use and if sequential, what gross motor skill-based activity can be introduced to enable the tactical personnel to sequentially shift from one sensor to the next if required due to battery or other form of failure. Tactical officers should practice this activity during training. Ensuring that any tasks performed relating to changes for data collection are gross motor skill based is important as elevated heart rates during an operation result in the degradation of fine motor skills, and with higher increasing heart rates, degradation of gross motor skills can occur [15].

Climate Tactical officers are deployed in communities with extreme climates. Any sensors that will be used in a tactical operation should be tested in those climatic conditions to ensure they will operate correctly within those contexts. For example, battery life of many forms of battery reduces in extreme cold climatic conditions.

Protective Equipment and Tools Paramilitary and military tactical personnel have a wide range of protective equipment and tools that they wear and have at the ready that cannot be obstructed or interfered with for their effectiveness by any introduced data collection equipment.

10.4 Data Acquisition

There are many challenges and opportunities in relation to the acquisition of data from devices worn or carried by paramilitary and military tactical personnel. These are outlined in the following subsections. Data acquisition enables data collected by data collection devices to be acquired for use by other systems such as those that provide health, wellness, resilience and adaptation assessment.

10.4.1 Data Frequency

The frequency of data acquisition is dependent on what is being monitored and the potential rate of change. For example, a signal rate of 250Hz is recommended when acquiring electrocardiogram data from an adult [16]. This enables the correct detection of the R peak and RR intervals from which a heart rate can be derived and heart rate variability can be determined.

Given the speed and dynamic nature of tactical operations, a signal speed of 1Hz will likely be required for dynamic activity data within the theatre of operation.

Climatic data is an example of one form of data that could be sampled at a lower frequency. This assumes the rate of change of the climatic conditions is not at a speed that would warrant data collection every second (1Hz). We demonstrated the collection of climate data from an integrated set of climatic chambers at a rate of a reading every 2 s (0.5Hz) in our prior research creating new forms of extreme climate acclimation resilience assessment and development training for military personnel [8].

10.4.2 Data Availability

The availability of data from various sensors for acquisition is dependent on the ability of the device to output the signal in a manner that aligns with the data acquisition process proposed. This is an important consideration during device procurement.

10.4.3 Shift-Based or Individual Devices

A logistical challenge in relation to the collection of data from tactical officers is who is wearing/carrying what instance of each device at any given point in time. Similarly, to the issuing of weapons on an individual basis to paramilitary and military tactical personnel, consideration needs to be given on a device model basis to determine devices that should be rotated to on shift personnel and those that need to be issued to individuals. Where the device is reporting on the status of the individual and that status has a longitudinal element, such as the use of health monitoring equipment, then the kit should be issued to an individual. This would then be similar to other personalized kit equipment and time does not have to be spent allocating and releasing sensors to tactical officers at the beginning and completion of each shift.

10.4.4 Device Battery Life

Device battery life is an important consideration for the effective capture of data during a regular routine shift as well as during training activities. Carrying secondary monitoring devices in many cases is not practical as they would need to use fine motor skills to switch the monitors and remove or move body armour putting them at risk of injury. As a result, battery life on data acquisition devices needs to support a single working shift or training activity with the ability to support extended live operations as required.

10.5 Data Transmission

The transmission of data from the theatre of operation whether in a live deployment or during training provides intelligence to those commanding the operation, and however, it can have significant security challenges. Physiological, psychological, sensory, stressor, environmental and activity data are required to be transmitted in real time. ‘The single most important challenge for IoT implementation across the military is security. IoT can be used to collect and transmit data on the position, disposition, and movements of troops and materiel’ [3].

Important considerations for data transmission within this context are outlined in the sections below.

Type Transmission of data in real time can occur via a range of transmission protocols such as Bluetooth, TCP/IP—the protocol used by the Internet, cellular and infrared.

Encryption Transmitted data will require the use of encryption to secure the transmitted messages.

Data Volume and Bandwidth Tactical operators deploy in teams. The bandwidth of the networks used to transmit the data from the various devices worn and/or carried by tactical operators needs to be correctly sized to ensure data from all sensors can be streamed effectively in real time.

Security Within paramilitary and military tactical personnel contexts, a key challenge for data transmission is security. Information technology equipment carried by tactical personnel, including health monitoring sensors that have transmitting functionality, can be used to collect and transmit data on position, disposition and movement through signal triangulation. They provide a significant web of entry points for cyber-attackers. This can have life-threatening implications for paramilitary and military tactical personnel if that transmission gives away their position to the enemy combatants or other hacker. In addition, the signal from IoT-based sensors could be manipulated or disrupted in some other way such as using radio frequency jammers, for example, corrupting vital intelligence about the theatre of operation that is being used by commanding officers for decision-making as they command the operation. ‘Many IoT devices are small and have limited capacity, have no human interface or interaction, and depend on real-time integration of data. This complicates traditional approaches to security like compartmentalized architecture, advanced encryption, and multiple authentication, which can slow down or prevent the exchange of data between devices and systems on the network, require more computing power on devices to decrypt data or authenticate regularly, or require human input for authentication' [3].

Redundancy A data transmission design for tactical officers needs to consider what degree redundancy is required. Redundancy can be provisioned through enabling support for different types of network communication for example or different routing of signals. If redundancies in data transmission are introduced, security of the multiple transmission pathways is required. Multiple transmission pathways can enable detection of signal tampering.

10.6 Data Integration

The integration of paramilitary and tactical personnel data from either live operations or training simulations within an analytics platform is a Big Data problem. This section outlines key considerations when considering the function and role of data integration.

10.6.1 Data Structures

Data structures for transmission of streaming data from live and training activities need to be standardized to ensure easy and effective integration of data. Interoperability is a key factor within this context given the broad and diverse forms of data to be integrated. A key challenge is not just the integration of data from legacy systems with new operation equipment and systems, but ensuring that new equipment and systems utilize the required standardized protocols for data exchange.

10.6.2 Device Procurement

Device procurement for paramilitary and military tactical officers is usually through a tender process. As such the tender documents should clearly outline expectations for data acquisition requirements from the device to ensure that the data is available for acquisition and integration with other data from the training or live operation.

In recent years, Canada has introduced an alternate form of procurement that enables first-of-a-kind procurement through the Build in Canada Innovation Program which has now been consolidated under the Innovative Solutions Canada Program's Testing Stream.[3] This program enables government departments to

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[3] https://www.ic.gc.ca/eic/site/101.nsf/eng/00064.html.

pursue an alternate path to try newly proposed equipment outside of traditional procurement processes.

Tender processes and alternate forms of procurement should ensure that device output data formats and transmission protocols required are clearly outlined in the documentation for procurement.

Data architectures should enable direct transmission of data from the device to integrated secure cloud-based analytics platforms. Many consumer devices have a data architecture protocol that requires transmission of data to a proprietary cloud storage and analytics infrastructure from which a subset of data or in some cases all the data acquired can be downloaded in some periodic way after acquisition. This acquisition is often retrospective, manual and cumbersome. This form of architecture for data acquisition is not well suited within this context.

10.7 Data Analysis

Data analysis enables the creation of information and knowledge from the physiological, psychological, environmental, activity and other data collected from live deployments and training simulations performed by paramilitary and military tactical personnel. This information and knowledge should be created for the individual as well as for various population sets. Population-based analysis should be stratified by a range of factors including biological sex and gender constructs.

As noted in the previous chapter, tactical personnel are impacted physiologically and psychologically in the moment and longitudinally as a result of the operations they carry out and the load they have to carry on an ongoing basis while working. Hence analytics should be created to support the analysis of their physiological and psychological response in order to assess health, wellness, resilience and adaptation.

Published research studies performing analysis on paramilitary and military tactical personnel are limited due to the classified nature of their operations and tactical approaches. The majority of published research to date on paramilitary and military tactical personnel has focused on population-based assessment of load carriage and physical fitness (refs), resilience and mental preparedness training [6] and to assess the impact of effectiveness of Andersen's work.

10.7.1 Health and Officer Down Analytics

Overall health and the detection of office down events are key analytics to provision during live deployment and training. The ability to alter resourcing of a deployment based on current physiological response may improve the success of these operations as well. This form of analysis can support live operations as they unfold in addition to their use in training. Body worn sensors enable the provision of information for ‘officer down’ situations and can enable enhanced situational awareness for higher levels of command in the theatre of operation.

10.7.2 Fitness Analytics

Fitness is an important form of analysis for the assessment of general cardiovascular and musculoskeletal performance. Fitness analytics enables assessment of overall cardiac health and assesses the health of high-risk areas of the musculoskeletal system such as shoulders, hips, ankles and knees.

Fitness assessment was performed through the retrospective analysis of survey data [17] that gathered demographical information about height, weight, rank, age and sex along with the weight of their kit (body armour, weapons, equipment). Information about the frequency, importance and perceived difficulty of 20 tasks were recorded. The details about their physical fitness program were gathered as well. Muscle strength, body mass index (BMI), endurance, aerobic and anaerobic power and agility were assessed to determine population-based performance scores [18].

10.7.3 Resilience Assessment and Development

Resilience assessment provides a mechanism to assess an individual and population ability to cope with various stressors and environmental factors from the theatre of operation in live or training scenarios. Resilience enables improved ‘in the moment’ responses due to reduced nervous system response to the situation and has great potential to reduce post-traumatic stress injury after the deployment or training scenario.

At present, assessment of resilience is limited to research studies and is not currently a regular training protocol for paramilitary and military personnel, and hence there is great potential to create information technology and engineering solutions that provision the capacity to assess resilience as part of standardized training procedures.

Population-based assessment of resilience needs to stratify the population based on biological sex, gender, race, age and level of experience to name a few key population factors that have great potential to differentiate performance levels and provide insights in relation to the development and retention of resilience.

Resilience development was assessed in a research study across a population of 18 male tactical officers through the analysis of the change in average heart rate and maximum heart rate while listening to critical incidence levels before and after a mental preparedness training intervention that introduced a controlled breathing technique. The analysis was performed at the population level only [7].

McGregor proposed Athena, a Big Data platform enabling data collection, acquisition, integration, analysis and visualization of physiological and activity data. It represents the instantiation of a pioneering data warehousing and artificial intelligence design. Athena is an extension of Big Data analytics-based Artemis platform. Artemis, named after the Greek goddess of childbearing, is a Big Data analytics platform proposed by McGregor that enables concurrent sensor processing from multiple entities for real-time analytics of multiple data streams and contains innovative artificial intelligence-based approaches to determine patterns in physiological data both in real time and retrospectively [19–21].

Athena was initially demonstrated via a case study that integrated trainee physiological data with data from ArmA3, a first person shooter video game and a haptic garment [13]. Within that work, heart rate was correlated with events occurring within the game to demonstrate physiological response to a range of skills and stressors.

Additional resilience assessment involving heart rate variability, blood oxygen saturation levels and other physiological responses will be reported in our future publications.

10.7.4 Wellness

In addition to the assessment of resilience, analytics can be created to assess longitudinal deviations in wellness that could demonstrate the onset of various mental health conditions such as depression, anxiety and post-traumatic stress. Systemic approaches to provision wellness analytics have not yet been provisioned for paramilitary and military tactical personnel.

10.7.5 Acclimation, Adaptation Assessment and Development

Paramilitary and military tactical personnel can be deployed to operations in varying climatic conditions, sometimes with little warning and potentially for extended periods of time. Ensuring they are acclimated to performing in those climatic conditions is important as a result.

McGregor's Athena platform was extended to integrate real-world activity data, environmental data and physiological data within a research study demonstrating its use for extreme climate acclimation assessment and development in addition to resilience assessment and development within controlled climate deployment simulation scenes [22]. Within that work, heart rate was assessed based on the Grossman heart rate ranges [15] together with minimum, maximum and average heart rates for each activity in the deployment sequence.

10.8 Data Visualization

Data visualization enables information and knowledge exploration through passive visualization as well as active visual analytics.

The data visualization approach needs to ensure that the tools used for visualization deliver the right information to the right people in various roles at the right time through the right device and software tool.

There are a number of different roles within this context that require information to be visualized during training and live operations such as the Tactical Officer, the chain of comment such as the sergeant, staff sergeant and director, medical support and trainers who are present during training activities. Each has a set of metrics they are responsible for that necessitates their ability to receive information relating to those metrics.

However, the acquisition of physiological, psychological, activity, load carriage, environmental and other data including stressors has significant risk of data overload. As a result, effective approaches for the synthesis and analysis of this data for individuals and the population are paramount for effective outcomes. To date, the focus of analytics within the paramilitary and military population has focused on retrospective population-based assessment of fitness, skill and resilience. As a result, visualizations have been created retrospectively to guide overall policy for training and fitness development.

We have demonstrated that McGregor's Athena platform has the functionality to provide individualized visualizations and visual analytics tools that display individualized performance information based on heart rate behaviours for each of the activities within the deployment scenario [22]. There is great potential for such systems to be used for skill training, fitness assessment, resilience development and pre-deployment acclimation generally.

10.9 Solution Deployment

Defence forces in many countries are recognizing the need for a strategic plan to create systemic approaches to monitor their military personnel. Military tactical personnel as a subset of military personnel benefit from these systemic approaches within the larger organization. In particular, there is a recognition for the need to utilize diverse forms of streaming data from soldiers and the theatre of operation within the paradigm of the Internet of Things (IoT). As an example, a United States report outlines the opportunities to utilize the IoT for a more efficient and effective military [3].

Similarly, paramilitary personnel who are within police departments can benefit from systemic approaches within the larger police department but require additional tailored solutions for the tactical context.

However, the same benefits of economies of scale are not as apparent for paramilitary groups that operate outside of police departments. As a result, methods to enable economical solutions for the provision of this form of monitoring together with data analysis for paramilitary and military personnel require careful strategic planning and information technology resources support.

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Chapter 11
Ultrasound for the Emergency Department and Prehospital Care

Lars A. Gjesteby, Joseph R. Pare, and Laura J. Brattain

11.1 Introduction to Medical Ultrasound

Medical ultrasound uses high frequency sound waves, typically in the range of 3–18 MHz, and their echoes, to form a cross-sectional spatial map of tissue boundaries based on impedance differences. It has utility in many applications including thoracic, abdominal, cardiac, gynecological, urological, and musculoskeletal examinations, as well as interventions and procedure guidance [1]. The real-time aspect of ultrasound is particularly helpful in capturing tissue dynamics and blood flow (i.e., through Doppler ultrasound). Technological developments in the last few decades have enabled portable ultrasound to expand into new fields of medicine and care environments. The modality is used across all levels of care, spanning from point-of-injury and field hospitals to established large medical facilities. Portable ultrasound is particularly well suited for extreme environments due to its portability, small form-factor, ease of use, and versatility. It has the potential to provide ambulatory, long duration, and non-intrusive monitoring with real-time biofeedback [2].

There are several modes of ultrasound imaging that can provide real-time insight into anatomical structure and function within the body. Two-dimensional (2D) B-mode, or brightness mode, is the most commonly used ultrasound mode in which a cross-sectional image is formed with intensities proportional to the amplitude of

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the returning echoes. 3D B-mode imaging is also available on some ultrasound devices with matrix array transducers. Alternatively, to study temporal information and movement of a region of interest, M-mode (motion mode) employs a single scan line for emitting and receiving ultrasound waves and stacks the one dimensional data along the time axis to display motion. Additional dynamic imaging modes are color and power Doppler, which use ultrasound pulses to detect the magnitude and direction of blood flow to assess the functional state of the vascular system. Contrast-agents produce non-linear echoes at specific frequencies, which can be separated from background tissue echoes. These microbubbles are valuable for visualizing hemorrhage and can even be used as a vehicle for therapeutic agents to be released at a desired location by ultrasonic rupture. Finally, shear wave elastography is a quantitative ultrasound technique to measure tissue biomechanics including stiffness, which has applications in many areas including the assessment of breast tumors, liver fibrosis, and musculoskeletal injuries.

The traditional cart-based ultrasound machine is standard equipment in hospitals and is often capable of acquiring medical images using various modes with high image quality. With tradeoffs in acquisition options and image quality, much smaller form factors are available on tablets and smartphones to enable more efficient use at the bedside. There even exist wireless transducers paired with smartphones that are ideal for imaging directly at the point-of-injury. The various imaging modes and sizes of ultrasound devices all play a role in enabling different levels of medical care in multiple extreme environments. In this chapter, we will focus on the importance of portable ultrasound in the emergency department and for prehospital care in both civilian and military settings.

11.2 Ultrasound in the Emergency Department

11.2.1 Emergency Department Environment

The Emergency Department (ED) is a unique extreme environment and can often appear to be in a state of controlled chaos. The ED is distinctive compared to other medical departments in that it is a location with many medical specialties that can care for a variety of patients across all ages. For example, one encounter could be for an elderly person suffering chest pain and the next for a child with an extremity injury after falling from a bicycle. There can seemingly be a numerous array of diagnostic tools available to the healthcare professional, but depending on the setting, the capabilities of the ED may vary greatly. This difference may influence how imaging studies are selected to deliver patient care. Small, rural, or free-standing EDs may have limited diagnostic tools available and may only have the ability to perform radiography or ultrasound. In this section, we review several example applications in which ultrasound alone can provide key diagnostic information and procedural guidance.

Table 11.1 Core health areas defined by ACEP in 2016

Core ACEP ultrasound applications		
1. Trauma	5. Biliary	9. Thoracic
2. Pregnancy	6. Urinary Tract	10. Ocular
3. Abdominal Aortic Aneurysm	7. Deep Venous Thrombosis	11. Bowel
4. Cardiac & Hemodynamic	8. Musculoskeletal & Soft Tissue	12. Procedural

11.2.2 Applications of Ultrasound in Emergency Department

The conditions and health issues encountered in the ED can range from mild to life-threatening, and ultrasound imaging provides insight into many of them. The American College of Emergency Physicians (ACEP) defines 12 core applications (Table 11.1) for point-of-care ultrasound (POCUS) [3]. In this section, we will cover a few most common ones. It is important to note the difference between a comprehensive ultrasound exam and one that is a point-of-care examination. A comprehensive ultrasound exam is frequently performed in the Radiology Department or Cardiology Department. It contains a detailed and often extensive examination of the particular organ(s) of interest. In contrast, a POCUS exam is often considered a brief focused assessment performed at the bedside by the treating healthcare professional to answer limited clinical questions. For example, a POCUS would be performed to detect bleeding in the abdomen in the setting of trauma, but it would not be a comprehensive report of each abdominal organ with findings unrelated to the reason for performing the exam. In this section, we will discuss medical and traumatic emergencies that relate to POCUS for ED care. For each case, a medical diagnosis or concern will be provided along with discussion for the related ultrasound examination and relevant findings.

11.2.2.1 Trauma Assessment

The ED often encounters patients suffering from physical trauma. Trauma is the result of physical injury and is classically categorized as penetrating or blunt but can also include environmental injuries. Penetrating trauma is, as implied, an injury that results from loss of integrity of the skin, which may be caused by a stab wound or gunshot wound. The end outcome is direct harm that often causes hemorrhage, fractures, or tissue injury. The physical injury, as a result of the penetrating force, causes damage in the trajectory of the object. The most concerning injuries are those to vital organs and those that result in uncontrolled hemorrhage. Other organs which may not result in significant bleeding but are of importance include the bowel and urinary system. Penetrating trauma to the chest can injure the heart, lungs, or major vasculature. Injury to the heart can result in bleeding into the sack around the heart, causing a pericardial effusion (hemopericardium), or direct cardiac laceration. In pericardial effusions from hemorrhage, blood pooling pressure can limit filling of the heart. This condition is called cardiac tamponade and is life-threatening. Injury to the lungs may result in lung lacerations and also pneumothorax, which occurs when air enters the pleural space, causing the lung to collapse. If air keeps collecting in the space around the lung, this can lead to increased pressure in the thorax. The accumulated pressures can impair blood return to the heart, termed tension pneumothorax, which is also life-threatening. When a lung collapses it compromises the body's ability to deliver oxygen and remove metabolic waste products. Penetrating trauma to the head, neck, and limbs can also result in catastrophic outcomes. Blunt trauma is often the result of an external force causing injury but not resulting in direct penetration into the body. A common example of blunt trauma includes car accidents. As with penetrating trauma, blunt trauma injuries will often be found in the location where the external force is exerted, and as with penetrating trauma, blunt trauma can result in hemorrhage, lung collapse, broken bones, and damage to tissue and organs.

A widely utilized application for trauma with ultrasound is the "FAST" exam: Focused Assessment with Sonography for Trauma [4]. This exam uses ultrasound to assess four anatomic locations for signs of hemorrhage. It is important to note fluid, including blood, generally appears as a hypoechoic black region (low intensity) on an ultrasound image. The four views include a right upper quadrant view (around liver and right kidney, and base of right lung), a left upper quadrant view (around the spleen and left kidney, and base of left lung), a lower abdomen view (near bladder, bowel, and uterus, if applicable), and a subxiphoid cardiac view. Figure 11.1 shows a right upper quadrant abdominal view depicting free-fluid (FF) in the right lung base and a small strip of fluid near the liver. Even the smallest strip of fluid around the liver may equate to upwards of 600 cc of blood having already been lost [5]. In patients with blunt trauma, the FAST exam is performed to detect signs of intra-abdominal or intrathoracic hemorrhage. This technique helps to identify life-threatening bleeding, determine whether further advanced imaging such as a computed tomography (CT) scan is appropriate, and expedite time to definitive care in the operating room [4]. The extended FAST exam, or eFAST, also

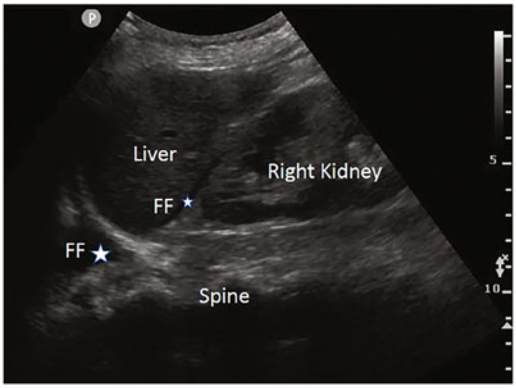


Fig. 11.1 Example ultrasound B-mode image of free-fluid (FF) as a result of trauma

includes assessment of the lungs for pneumothorax detection given that ultrasound outperforms chest radiograph for this purpose in supine patients [6, 7].

Limitations of the FAST and eFAST exams include those related to possible incorrect interpretation of findings. Pitfalls may occur when examining patients who have known or unknown pathology, which could cause the physician to make an error in clinical reasoning. For example, a patient with cirrhosis can have abdominal ascites, which may appear similar to intra-abdominal blood from hemorrhage in an ultrasound image, resulting in improper management. While we are unable to discuss all the pitfalls and considerations for point-of-care ultrasound in this chapter, there are numerous excellent, open-access medical education resources available for further learning [8, 9].

Although the eFAST exam has become a standard of care for the evaluation of blunt trauma patients, the use of eFAST for penetrating trauma is more controversial. This is because additional diagnostic testing is often required in patients with penetrating wounds to support clinical reasoning. Nonetheless, benefits of ultrasound for penetrating trauma assessment have been demonstrated [10]. In the authors' experiences, the eFAST exam can be particularly helpful in penetrating trauma. As an example, when considering a gunshot wound to the center of the chest, it can be difficult to tell if the bullet may have injured the organs above or below the diaphragm, or both. In a patient where each second is critical, being able to rapidly assess for the most concerning injuries is important. Ultrasound can be used to quickly evaluate for cardiac injury, lung injury, or intra-abdominal hemorrhage. When attempting to stabilize a dying patient with any of these three injuries, emergency care includes surgical entry into the abdomen or chest. The use of ultrasound can help prioritize surgical needs based on bedside imaging results.

11.2.2.2 Abdominal Aortic Aneurysm Diagnosis

Abdominal aortic aneurysm (AAA) is the enlargement of the abdominal aorta. There are two types of AAA that can occur: fusiform and saccular. The fusiform type is the most common and is characterized by bulging or ballooning on all sides of the aorta, whereas the saccular type AAA bulges out on only one side. Most abdominal aneurysms develop distal to the renal arteries. As an aorta dilates excessively, the risk of rupture and resultant catastrophic hemorrhage increases [11]. An abdominal aorta with diameter >3 cm is considered pathological [12]. There are specific recommendations about whether procedural intervention is necessary based on rate of increase in size and overall size. For example, repair may be required when AAA maximal transverse diameter is greater than 55 mm for men or 50 mm for women, or annual AAA growth rate is greater than 10 mm/year [13, 14].

The AAA exam is performed with B-mode ultrasound in the ED to determine pathology associated with chest pain. The abdominal aorta is often imaged from the diaphragm down into both iliac arteries. Any location where the ultrasound does not image the aorta or iliac vessels poses a risk for missed pathology. It is important to image the aorta in sagittal as well as transverse views to avoid missing aneurysms.

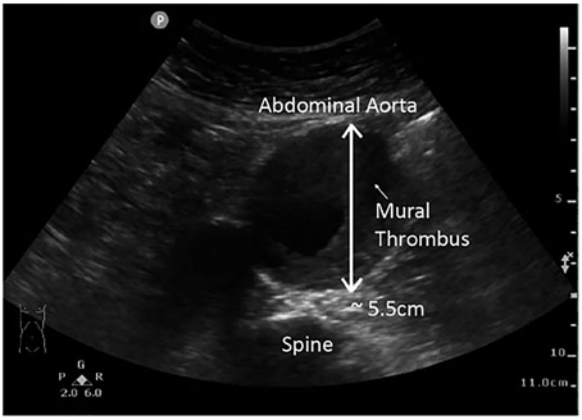


Fig. 11.2 Example ultrasound B-mode image of an abdominal aortic aneurysm

Doppler mode can also show areas of blood flow to further elucidate aorta size. Once detected, an AAA should be measured from exterior wall to exterior wall of the vessel. Figure 11.2 shows an AAA that measures approximately 5.5 cm with a mural thrombus present. A thrombus is a blood clot formed in situ within the vascular system of the body and can impede blood flow. When it attaches to the wall of a blood vessel or the cardiac chamber, it is called mural thrombus. Measuring only the internal lumen of the aorta poses a risk to missing a mural thrombus. The AAA exam can be technically challenging to perform due to occluding structures, such as the bowel, and abdominal girth, as extra subcutaneous fat can limit penetration of the ultrasound beam. Firm gentle pressure can help to visualize deeper abdominal structures, but this technique is not always able to overcome technical or physical limitations.

11.2.2.3 Deep Vein Thrombosis Detection

Deep vein thrombosis (DVT) refers to the presence of a blood clot within a deep vein of the body, most frequently in the lower extremities, such as the legs. Leg swelling and pain can represent symptoms of a DVT, which may embolize due to the clot becoming dislodged and propagating throughout the body. DVTs can travel to the lungs causing a pulmonary embolism, which can block forward flow from the heart (obstructive shock) or lead to impaired oxygenation (hypoxia), both of which are life-threatening. Additionally, smaller clots can pass through holes in the heart if cardiac defects are present and result in arterial infarcts or strokes depending on where the clot comes to rest. Therefore, identification and treatment of thromboses and other clots are an important clinical necessity.

POCUS ED recommendations initially focused on a two-point compression scanning technique to diagnose a lower extremity DVT using ultrasound. For a two-point DVT scan, hand compression is applied near the groin and then again behind the knee, each followed by a ultrasound scan. Further research suggested that this two-point approach can result in missing 6% of isolated DVTs [15]. Therefore, a full DVT scan was recommended to be conducted from groin to calf with a goal to image as much of the vessels as possible [16]. As with AAA (Sect. 11.2.2.2), any area of the vessel not imaged can result in missing pathology. There are also additional techniques such as calf compression and using Doppler to assess for more distal and proximal thrombus. When a DVT is found, treatment with anticoagulation should likely be started if there is not a contraindication [17].

11.2.2.4 Cardiac and Hemodynamic Assessment

One focused clinical approach to point-of-care cardiac and hemodynamic ultrasound in the ED is the assessment of the five “E’s” [18]. The five “E’s” include effusion (as discussed in Sect. 11.2.2.1), ejection (left ventricle contraction), equality (size of the right ventricle compared to the left ventricle), exit (thoracic aorta size), and entrance (inferior vena cava, or IVC). A pericardial effusion can result from trauma and bleeding; however, it can also occur in numerous other disease states that cause blood or other fluids to collect in the pericardial space, and can lead to cardiac tamponade. Other examples of effusion include pus in the setting of infection, or serous fluid in the setting of cancer or advanced renal disease. Figure 11.3 demonstrates a pericardial effusion imaged by B-mode ultrasound. The treatment may require emergency removal of the fluid if causing hemodynamic compromise, which could be guided by ultrasound. Ejection refers to the left ventricle contraction. In the setting of heart attack or heart failure, poor ejection is a sign of cardiac disease. Ultrasound can be performed on patients with cardiac arrest to determine if there is evidence of cardiac activity. Equality of right and left ventricle sizes is important as a marker of right-sided intracardiac pressures. Submassive and massive pulmonary embolism or severe pulmonary hypertension can lead to pathologic cardiac findings detected by ultrasound. In these disease states, the size of the right ventricle can become larger than the left ventricle, which is abnormal. Exit refers to assessment of the proximal thoracic aorta with ultrasound. This portion of the aorta can become enlarged (as with AAA), and >4 cm is abnormal and >4.5 cm is aneurysmal. A dilated thoracic aorta can result in rupture and can also be a marker for thoracic aortic dissection, which when left untreated is almost always fatal. Lastly, the entrance refers to the hemodynamic state of the IVC, which is a marker for central venous pressure (CVP). The degree of collapse of the IVC measured by ultrasound (B-mode and Doppler) provides relative estimates for the CVP. An elevated CVP is indicative of possible fluid overload, such as with heart failure. Conversely, a low CVP can be a marker for volume depletion, such as with sepsis or dehydration. The use of the IVC and cardiac assessment can help to direct fluid management and clinical decisions when caring for patients in many scenarios [18].

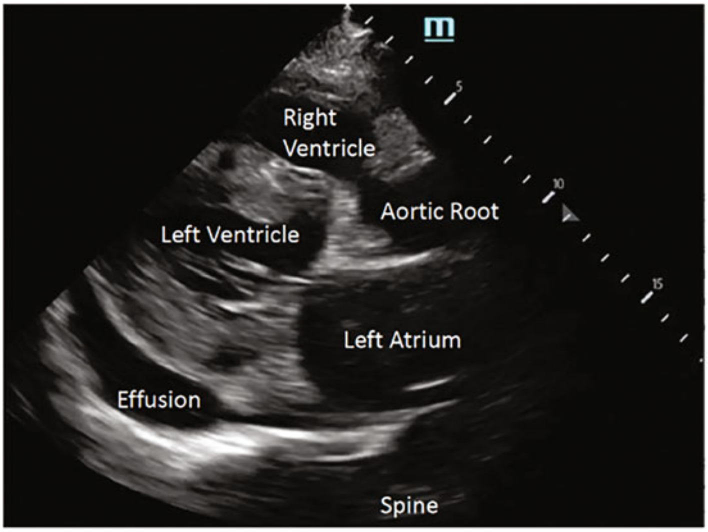


Fig. 11.3 Example ultrasound B-mode image of pericardial effusion

11.2.2.5 Procedural Guidance

The use of portable ultrasound for procedural guidance increases efficacy and safety by allowing real-time procedure planning and non-invasive visualization of patient anatomy [3]. Radiologists have been using ultrasound to guide procedures routinely [19]. Specifically, ultrasound guidance is playing an increasingly important role in basic procedures such as peripheral and central intravenous access, arterial access, suprapubic aspiration, abscess incision and drainage, foreign body identification, nerve blocks, and joint arthrocentesis [20]. In addition, it is used extensively in more complicated interventions such as heart valve repairs and atrial fibrillation ablations [21]. Similarly, ultrasound procedure guidance can greatly improve procedural success in the ED with regard to a number of procedures that need to be acted upon in a timely fashion, such as central line placement and abscess incision and drainage [22]. It is important to remember to practice proper safety guidelines during these procedures and to use a recommended probe cover if needed for each application to avoid iatrogenic infections.

11.2.3 Summary

Through this section we have covered several of the 12 core ultrasound applications in a brief overview. This is an introduction to the use of ultrasound for the care of patients in the ED and is not an exhaustive review of ultrasound for emergency medicine. We encourage the reader to explore the vast open-access medical education resources that are available online. Based on location, resources, training, and other factors, different healthcare professionals may approach patients in different ways. We find that ultrasound is a safe and important diagnostic tool when utilized properly to deliver healthcare.

11.3 Ultrasound for Prehospital Care

11.3.1 Prehospital Environment

The prehospital environment is another extreme setting in which ultrasound can be a valuable tool. In this section, we discuss prehospital care in the context of both civilian and military environments. Civilian prehospital scenarios can include the point of injury at traumatic accidents and in the back of an ambulance. Natural disasters, such as earthquakes and hurricanes, and mass casualty events, such as shootings or explosions, also necessitate urgent care in prehospital settings with limited equipment and medical expertise. In the military context, the prehospital environment may be remote battlefields such as deserts, jungles, subterranean areas, and mega cities. In all cases, prehospital care faces challenges due to limited supplies, limited medical personnel, and an urgency to perform life-saving interventions or critical stabilization procedures. The extreme nature of battlefields can also be exacerbated by lack of communications and lack of supporting forces.

11.3.2 Applications of Ultrasound in Prehospital Settings

Ultrasound is rapidly becoming an essential point-of-care (while the patient is being treated) and even point-of-injury (immediately after the patient is injured) tool for assessment and triage of trauma due to advances in portability. Military settings are relying more on ultrasound imaging to guide vascular access, pneumothorax, and cricothyrotomy interventions [23]. Civilian prehospital environments have also benefited from ultrasound, including low- and middle-income countries without well-developed healthcare infrastructure. A systematic review found that hand-carried and hand-held devices aided in difficult medical scenarios for the diagnosis and management of life-threatening conditions [24]. During the Haiti earthquake disaster in 2010, ultrasound played a key role in patient care decisions for 70% of scans conducted [25]. Specifically, it influenced recommendation of medications and whether or not surgery or transfer to a higher level of care was needed. It was particularly useful in evaluating non-traumatic abdominal pain and parasitic diseases, and guiding procedures. Table 11.2 is a snapshot of the major medical complications in prehospital settings and associated ultrasound applications to be described in this section.

Table 11.2 Leading medical complications in prehospital extreme environments and associated ultrasound applications. CTM = cricothyroid membrane, MSKI = Musculoskeletal injury, FAST = Focused assessment with sonography in trauma, eFAST = Extended focused assessment with sonography in trauma, CAVEAT = Chest, abdomen, vena cava, and extremities for acute triage

Medical complication	Ultrasound applications
Trauma/Hemorrhage	FAST exam
	Identify blood vessels for vascular access
	Assess Doppler blood flow in pre-shock conditions
Loss of Airway	Identify landmarks on neck (trachea and cricothyroid membrane)
	Guide cricothyrotomy and tracheotomy
Pneumothorax	eFAST exam
	Visualize pleural region and lung sliding (or lack thereof) for possible collapse
MSKI	CAVEAT exam
	Assess severity of injury
	Localize area for stabilization
	Aid return-to-duty decisions

11.3.2.1 Hemorrhage Detection and Vascular Access

Hemorrhage, the release of blood from a ruptured vessel, can occur internally or externally to the body. Physiological complications arise when the bleeding continues undetected or uncontrolled and cannot be stopped by compression. Non-compressible hemorrhage, particularly truncal hemorrhage, is by far the leading cause of preventable deaths on the battlefield [26]. In a recent special report from the Military Trauma System [27], four of the top 10 research priorities for forward surgical care were in the category of "Resuscitation and Initial Hemorrhage Management."

In both military and civilian cases, non-compressible hemorrhage is addressed by vascular access. For central line placement, typically a needle is first inserted into a central blood vessel, such as the common femoral vein/artery, internal jugular vein, or subclavian vein, to establish the access. A peripheral vein in the upper arm could also be a targeted access point. The needle is exchanged for catheter placement, which can be completed with the Seldinger technique. Resuscitative fluids, blood, medication, and clotting materials can be passed through the catheter directly into the central circulatory system. One procedure known as resuscitative endovascular balloon occlusion of the aorta (REBOA) involves advancing a balloon catheter through the femoral artery and into the aorta to provide temporary control of hemorrhage. In prehospital settings, manual vascular access can be challenging and time-consuming to perform without expertise or assistive devices [28].

Ultrasound provides a critical role in addressing hemorrhage with its ability to detect free-fluid blood in abdominal regions and identify blood vessels for cannulation. Blood allows ultrasound waves to transmit more easily than surrounding tissue, so free-fluid will appear as dark, hypoechoic regions in the image. Similarly, arteries and veins have low echogenicity resulting in dark elliptical areas in the image. Common ultrasound techniques for visualizing a blood vessel are short-axis and long-axis B-mode scanning, and Doppler mode. In the short-axis approach, the transducer is oriented perpendicular to the vessel to provide a cross-sectional view. This technique is less sensitive to rotation of the transducer and off-axis movement. The disadvantage is that a needle inserted from the out-of-plane direction cannot be tracked throughout the process, and the tip only appears when it intersects the image plane. By contrast, in the long-axis orientation, a longitudinal view of the vessel can visualize the full path of a needle being inserted from in-plane. The difficulty is in finding and maintaining the long-axis vessel view in the image, due to sensitivity to transducer rotation and medial-lateral translation. Doppler mode allows identification of vessels by the presence of blood flow under healthy conditions, but hemorrhagic shock leading to hypotension may hinder this imaging technique.

Ultrasound protocols for detecting hemorrhage were adopted in the mid-1990s with the emergence of the FAST exam [29], as described in Sect. 11.2.2.1. A recent study was performed to evaluate performance of US Army combat medics in conducting the extended FAST (eFAST) exam, which includes an additional view of the pleural space. After a 3-hour training session, 40 medics, who were novice sonographers, effectively completed 160 eFAST exams with greater than 95% diagnostic accuracy and a mean time under 6 minutes [30]. However, another study found that in 274 patients with non-compressible torso hemorrhage, the FAST exam had a very high false negative rate at 49%, suggesting that exam results should not be solely relied upon to assess risk of shock [31].

Another comprehensive protocol for ultrasound-based trauma assessment is termed CAVEAT, which stands for “chest-abdomen-vena cava or vascular extremity in acute triage” [32, 33]. In addition to chest and abdominal imaging, more advanced screenings of the vascular system and skeletal extremities are included. Assessing a central vein, such as the inferior vena cava (IVC), provides insight into the intravascular blood volume and whether shock conditions are imminent. The diameter and the collapsibility index of the vessel are two metrics used to quantify hypovolemia and shock risk. However, locating the vein of interest can be challenging due to its small diameter (1–2 cm) and may take up to 5 minutes even for skilled sonographers [34].

After the identification of a non-compressible hemorrhage in a prehospital setting, the ideal next step would be to evacuate the casualty to a facility where well-trained medical personnel can perform vascular access and catheter placement to stop bleeding and resuscitate within 1 hour. If that is not possible, then a life-saving intervention needs to be performed in the extreme environment. Numerous studies have concluded that ultrasound guidance provides a critical advantage in efficiently inserting a needle into the internal jugular vein or femoral vein [28, 35, 36]. In addition to delivering higher first-attempt success rate, ultrasound greatly speeds up the procedure time and yields significantly fewer complications. Once the needle creates a path into the vessel, it can be exchanged for various types of catheters. Clinical protocols have been developed relying on ultrasound for insertion and guidance of the REBOA catheter to the abdominal aorta for short-term stabilization [37]. However, these are intended for trained experts in hospital settings. Enabling non-experts to perform REBOA in extreme environments at the point-of-injury has been the subject of a recent training program. In the simulated study, first responders, specifically fire fighters, were trained on endovascular and ultrasound skills and then asked to perform REBOA procedures on manikins start-to-finish [38]. When compared to Special Forces medics with prior baseline training, the fire fighters were able to achieve faster procedure times with more efficiency, indicating the effectiveness of the "just-in-time" training program.

11.3.2.2 Cricothyrotomy Guidance

Blunt, crushing trauma to the face can prevent a person from breathing through the nose and mouth. The jaw may no longer be able to open and close, and there may be swelling and blood pooling in the nasal passages. If intubation through the mouth and into the trachea is not possible, cricothyrotomy is performed as a last resort emergency procedure. Cricothyrotomy involves making an incision with a scalpel or a large over-the-needle tube through the skin and the cricothyroid membrane (CTM) and then inserting the tube into the trachea to establish a patent airway. Since standard tracheal intubation is the most common means of establishing an airway in an emergency scenario, cricothyrotomies account for only about 1% of all emergency department intubations and are used mostly in persons who have experienced an extreme traumatic injury [39]. This technique is only intended to be a temporary measure until a definitive airway can be established [39]. It is a high risk procedure; if done incorrectly (e.g., the tube is not placed in the trachea or a critical structure around the neck is punctured), it can be life-threatening by itself. Routine training is of great importance to maintain the competency to perform this process when called upon. Semi-automated capabilities that can assist the operator to perform this procedure promptly and correctly can also help ensure efficacy.

CTM is the target insertion location. It is an area of soft tissue in the neck between the harder thyroid cartilage and cricoid cartilage. Due to its low resistance, the CTM is an ideal location for a needle and breathing tube to pass through into the trachea. Palpation of the neck is often the first step to identify the membrane, but this method may fail in the presence of excess tissue or abnormal anatomy [40].

Although cricothyrotomy is a rarely performed process, it needs to be completed quickly and correctly under a high-stress situation when required. In civilian environments, transportation accidents and explosions can cause facial trauma that inhibits breathing through the nose and mouth. On the battlefield, blasts, gunshots, and other trauma result in similar situations. In all cases, due to urgency, the intervention must be performed prehospital at the point-of-injury. When intubation is possible, ultrasound can help confirm proper tracheal tube placement to avoid complications during ventilation [41]. When intubation is not possible and an airway entry procedure is needed, imaging can make the greatest difference for a cricothyrotomy as the CTM can be recognized in ultrasound from its position between two dark, hypoechoic cartilage areas.

A systematic review of cricothyrotomy protocols found many examples in which ultrasound greatly increased success rates for CTM localization [42]. One study reported that palpation of the CTM was successful in only 46% of mixed body mass index (BMI) patients and 37% of morbidly obese patients [43]. The physicians in the study were provided with 15 minutes of hands-on ultrasound training and asked to repeat the procedure. Ultrasound imaging significantly improved CTM localization success to 100% in the mixed BMI subjects and 83% in the morbidly obese group. In another study of CTM localization on mixed BMI patients, it was found that palpation and ultrasound success rates were not significantly different (67% and 69%, respectively) [44]. In this case, the novice operators conducting the scans received only brief training beforehand.

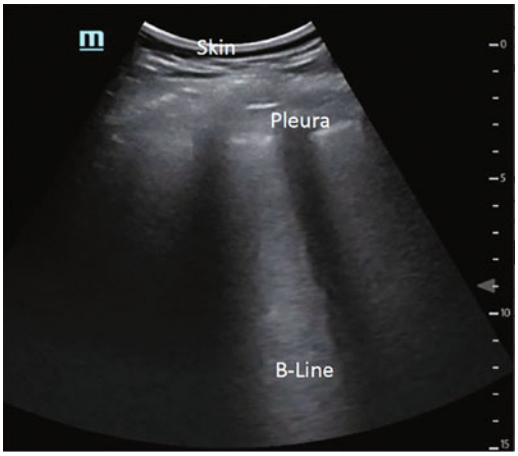
One specific ultrasound-based protocol was developed on cadavers and tested on live patients for identification of the CTM [45]. The transducer was placed on the neck, first in an orientation parallel to the trachea to find the thyroid cartilage, CTM, cricoid cartilage, and tracheal rings. The transducer was then moved laterally in both directions to determine the outer edges of the CTM. With the device re-centered on the CTM, it was turned 90-degrees to a transverse view of the CTM for confirmation. In fifty subjects, the mean time to complete the scan and confirm the CTM location was 24 s.

Clinical trials have also confirmed the value of ultrasound for CTM detection in abnormal neck anatomy, with 223 subjects randomly split between external palpation and ultrasound scanning groups [46]. Both methods compared the estimated CTM location to a ground truth reference established by a computed tomography scan of the neck. It was determined that ultrasound pinpointed the CTM within a mean distance of 3.4 mm, while palpation yielded estimated locations within a mean distance of 16.6 mm. Further, only 8% of the palpation group had the CTM successfully detected within 5 mm, compared to 81% in the ultrasound group. In a small cadaver study, ultrasound guidance was found to result in safer and more efficient first-attempt success of percutaneous tracheotomy [47].

11.3.2.3 Lung Injury Detection and Needle Decompression

We have previously covered traumatic injury to the chest and briefly discussed the role of ultrasound to assess for pericardial fluid, hemothorax, and pneumothorax in Sect. 11.2.2.1. In addition to these findings, thoracic ultrasound can assess for additional lung pathology. Ultrasound can detect viral and bacterial infections of the lungs. It can also be helpful to identify an empyema or pleural effusion. Additionally, one of the most useful applications for point-of-care lung ultrasound is to assess for signs of pulmonary edema, which is most often associated with heart failure. Pulmonary edema can cause shortness of breath and will often appear as B-line artifacts on ultrasound. Figure 11.4 shows an example of B-lines on lung ultrasound seen with lung pathology. B-lines can be seen in several conditions

Fig. 11.4 Example ultrasound B-mode image of B-lines in the lung



including infection, pulmonary edema, hemorrhage, interstitial lung disease, and acute respiratory distress syndrome. B-lines should be interpreted in the context of the medical history to determine what the etiology is for these pathologic ultrasound findings [48].

Another type of lung injury that may be encountered in prehospital settings is pneumothorax or tension pneumothorax, which are typically caused by a penetrating chest wound that creates a one-way valve, leading to air accumulation in the pleural space and eventually lung collapse. The high pressure that continues to accumulate within the chest can prevent blood from returning to the heart. Tension pneumothorax symptoms include chest pain, shortness of breath, and rapid heartbeat. It is classically characterized by hypotension and hypoxia. On examination, breath sounds are absent on the affected hemithorax and the trachea may deviate away from the affected side. To definitively diagnose tension pneumothorax, X-ray, CT, or ultrasound imaging may be used. However, in prehospital settings, especially on the battlefield, portable ultrasound is often the only available device. Once a tension pneumothorax is identified, the most common treatment is to insert a needle catheter into the pleural space on the affected side to release the trapped air. Typical entry points include the second intercostal space along the mid-clavicular line or the fifth intercostal space on the anterior axillary line [49].

The eFAST and CAVEAT exams include a scan of the pleural space to detect abnormal lung sliding indicative of a pneumothorax. In B-mode ultrasound images, the pleural line appears as a bright, hyperechoic line between two rib shadow regions. Distinct motion of the pleural line between subsequent frames indicates normal conditions, while lack of sliding indicates pneumothorax. M-mode images are acquired along a single line for transmit and receive, and the lines are stacked together over time to look for changes in a specific location. A wavy, granular M-mode image will be produced if the underlying anatomy is moving, which is indicative of a normal lung. The image will appear like a static barcode if the region is stationary, which suggests pneumothorax.

The utility of ultrasound for detecting pneumothoraces was assessed for physician assistants and military medics without ultrasound experience [50]. Participants received brief training on chest ultrasound methods and were then asked to image a porcine model that may have contained zero, one, or two pneumothoraces. Of the 22 total pneumothoraces, 21 were correctly detected. All normal lung conditions were correctly identified as such. The study resulted in 95.5% sensitivity and 100% specificity for ultrasound to detect a collapsed lung. The study further indicates that just-in-time training may be sufficient to enable non-experts to use ultrasound for life-saving assessments in prehospital settings.

Ultrasound was also used to determine optimal strategies for needle decompression to relieve a tension pneumothorax, particularly in assessing chest wall thickness and appropriate insertion length. At the time of a French study [51], the procedural standard was to use a 14-gauge, 5-cm needle catheter. In 122 French soldiers, it was found that the mean chest wall thickness measured 4.19 cm in the second intercostal space (ICS) and 3.00 cm in the fourth ICS. However, the chest wall thickness was measured at greater than 5 cm in 24.2% of soldiers at the second ICS, but in only 4.9% of soldiers at the fourth ICS. Thus, the existing protocols for needle decompression in the second ICS could fail in approximately 1 in 4 cases. A similar conclusion by an American study led to the Tactical Combat Casualty Care updating its recommendations to use a 14-gauge, 8-cm needle catheter for the decompression procedure [52].

11.3.2.4 Musculoskeletal Injury Assessment

There are many potential ultrasound applications for the assessment of musculoskeletal injuries (MSKI). Ultrasound can be used to assess tendons and muscles for injury or inflammation such as tendonitis. Ultrasound can also be used to evaluate joints for fluid, such as in the setting of infection or gout. It can also be used to assess for skin infections including cellulitis, superficial and deep abscesses, and even signs of air in the setting of necrotizing skin infections. There is even the utility of ultrasound to assess for fractures depending on the location and ability of the ultrasound to evaluate the area, although X-ray is still generally the standard of care for most suspected fractures [3]. The CAVEAT ultrasound protocol specifically includes extremity assessment for long-bone fractures [32]. Shear wave elastography is also becoming a valuable tool in measuring tissue biomechanics, including stiffness, which helps detect subtle musculoskeletal abnormalities [53].

Common types of MSKI include long-bone fractures, rotator cuff tears, and ligament and tendon sprains in lower extremities. Among military service members, acute ankle sprains are one of the most prevalent MSKI suffered and can potentially lead to long-term disability if not properly treated [54]. Although these types of injuries may not be life-threatening, proper diagnosis and treatment in extreme environments are important for several purposes. In civilian disaster situations, determining severity of MSKI will inform decisions about transportation to higher levels of care or whether the patient can be stabilized at the point-of-injury. In military settings, return-to-duty decisions hinge on an accurate assessment of the injury and healing progression. Common features of MSKI in ultrasound images include bone marrow edema, acoustic shadows, and effusions.

The feasibility of using ultrasound to diagnose long-bone fractures in prehospital and austere environments was validated in studies involving emergency medical technicians (EMTs) and US Army Special Forces medics [55, 56]. A fracture simulation model was constructed using ex vivo turkey bones and opaque gelatin, which blinded the personnel to the presence and location of the fracture. After a brief training session, twenty EMTs demonstrated a sensitivity of 97.5% and a specificity of 95.0% in detecting fractures with ultrasound. Twenty Army medics also achieved high marks, with 100% sensitivity and 90% specificity. Additional investigations have shown that ultrasound can be performed accurately in the battlefield environment to diagnose fractures and obviate the need for patients to be evacuated for radiography [57].

Another study investigated external fixation of long-bone fractures with Schanz pins using ultrasound on phantom models of the femur [58]. Three surgeons without prior ultrasound experience were given just-in-time training and then proceeded to diagnose the fractures, determine an adequate configuration for fixation, and effectively insert pins in the proper region for all test cases. Another report also confirmed that sonography can accurately guide Schanz pin placement in cadaver femur and tibia fractures by measuring protrusions [59]. Ultrasound has also been demonstrated for assessing wrist injury of the scapholunate ligament by measuring separation and presence of discontinuity. Specifically, a soldier in the field was able to be rapidly diagnosed without the need for transport to a facility to get X-ray [60].

Several case reports have demonstrated the capability of ultrasound to stabilize MSKI in austere civilian situations. In one case, a hiker had suffered dislocation of the glenohumeral joint in the hip, and ultrasound at the point-of-injury guided a lidocaine injection and confirmed that the swelling reduced enough to allow the patient to hike out of the wilderness without risking a rescue mission [61]. In another instance, an ultrasound-guided adductor canal block was performed on a patient who suffered a knee distortion inside a cave [62]. The procedure was performed at the point-of-injury while rescuers at the cave entrance provided feedback in real-time via video.

11.3.3 Summary

In this section, we discussed the major medical complications in prehospital extreme environments that ultrasound can help address. Table 11.3 highlights studies from the literature comparing success rates and total time of detection and localization procedures with and without the use of ultrasound. While the results of ultrasound guidance are promising, there remain challenges to enable widespread use in extreme environments, especially for prehospital care. Current limitations of ultrasound-based examinations include the reliance on having a skilled sonographer

Table 11.3 Benchmark metrics from literature of procedures performed unassisted and with ultrasound to enable prehospital care. US = ultrasound, CTM = cricothyroid membrane, PTX = pneumothorax, IJV = inter jugular vein, PV = peripheral vein, MSKI = musculoskeletal injury

Procedure	Success rate (unassisted)	Success rate (US)	Total time (unassisted)	Total time (US)
Vascular access	IJV: 89% [36]	IJV: 99% [36]	IJV: 147 s [36]	IJV: 35 s [36]
	PV: 33% [63]	PV: 97% [63]	-	-
CTM detection	37–46% [43]	83–100% [43]	110 s [64]	57 s [64]
	8% [46]	81% [46]	-	24 s (± 20 s) [45]
	43% [64]	83% [64]	-	-
PTX detection	-	95.5% [50]	-	-
MSKI detection	-	Fractures 97.5–100% [55, 56]	-	-

available to operate the device, acquire high quality scans, and interpret the images. As a result, ultrasound findings suffer from high intra- and inter-observer variability. In prehospital settings, less skilled or novice users may not have extensive training to perform the required tasks without assistance. Telemedicine can provide a means for an expert in another location to guide the on-site personnel and/or review acquired images, if communications are available and reliable. More robust solutions include semi-automated or automated devices equipped with advanced image processing algorithms and artificial intelligence (AI) to assist the user.

11.4 Applying Artificial Intelligence (AI) to Ultrasound Imaging

Assistive algorithms have great potential to enable non-expert sonographers to acquire and interpret ultrasound images in EDs and prehospital care. The amount of literature presenting machine learning and deep learning algorithms for detection, classification, and segmentation tasks in ultrasound images has greatly increased in recent years [65]. AI-enabled imaging systems ease the burden of difficult decisions under stressful situations and allow medics to deliver life-saving care with greater confidence by increasing speed and accuracy. In this section, we present recent progress in AI for ultrasound with a few representative applications and discuss challenges that must be overcome in the AI development process.

11.4.1 Recent Examples of AI-Enabled Ultrasound

Semi-automated and automated systems that identify blood vessels and perform needle insertion more efficiently remain critically important to address non-compressible hemorrhage, which is a leading cause of death in prehospital situations, especially on the battlefield. AI-enabled, ultrasound-guided vascular access is an active research area, with initial efforts demonstrating encouraging results. Deep learning algorithms to detect nerves and blood vessels from ultrasound video have been reported [66, 67]. An accuracy of 94.5% was obtained in a dataset containing femoral vessels from 15 subjects. A more recent study focusing on robotic vascular access achieved substantial gains over manual methods for both peripheral vein detection and needle insertion [68]. Specifically, the first-attempt success rate to deliver a needle into a rat tail vein model was just 58.3% with fully manual methods, while deep learning-based ultrasound localization of the vessel and robotic insertion achieved 87.1% success. The deep learning architecture incorporated a recurrent fully convolutional network in order to track landmarks temporally in subsequent ultrasound frames.

Advanced image processing and deep learning methods have also been developed to automate the diagnosis of pneumothorax and tension pneumothorax with ultrasound. A 2016 study analyzed 133 bedside ultrasound examinations of the thoracic region, which were collected by medical personnel with a wide variety of experience, including students, fellows, and physician assistants [69]. The B-mode video clips were assessed by an image processing algorithm called iFAST, which first detected the pleural line as a hyperechoic region between the ribs and then looked for pixel movements to determine whether or not the lung was sliding as normal. The results indicated that pneumothorax was detected with 79% sensitivity and 87% specificity on the full dataset. Since the skill level of the sonographers varied, there were large differences in image quality between scans. When extracting 20 ultrasound clips with the highest image quality, the system achieved 100% sensitivity and 92% specificity in detecting pneumothorax.

A deep convolutional neural network (CNN) based on the VGG16 architecture was developed to further improve diagnostic accuracy of pneumothoraces compared to iFAST [70]. Convolutional layers pretrained on the ImageNet database were used as a starting point, and the last four layers and a fully connected layer were fine-tuned on a porcine ultrasound database containing 16,212 B-mode and 1868 M-mode thoracic images. A validation set was then used to evaluate the models. On 4053 B-mode frames (2030 with pneumothorax and 2023 normal), the CNN achieved 99.9% sensitivity and 99.7% specificity, while the iFAST algorithm yielded 85.7% and 82.6%, respectively. On 467 M-mode images (233 positive and 234 normal), the CNN classified pneumothoraces with 99.6% sensitivity and 97.0% specificity, versus 98.2% and 96.2%, respectively, for iFAST.

Another study assessed more advanced deep learning algorithms on 3-second thoracic ultrasound clips of porcine models [71]. All frames of the B-mode video clips were processed together to determine presence of pneumothorax using several techniques including optical flow, recurrent neural networks, and a fusion architecture leveraging M-mode reconstruction of the clips. Despite only training on data from three separate porcine subjects, the four algorithms achieved sensitivity in the range of 78–84% and specificity in the range of 82–87%. A total of 130 positive videos and 122 negative videos were used in the test set. The sliding of the lung over time (or lack thereof) is the most relevant feature in detecting pneumothorax, so it is logical to employ methods that utilize temporal information from an entire video clip to make diagnostic decisions.

An emerging area of research is applying AI and deep learning methods to diagnose and monitor a wide variety of musculoskeletal injuries and healing progression. One recent example used deep CNNs to estimate changes in active and passive skeletal muscle states of the calf [72]. Additional studies have focused on Achilles tendon injuries, with success in classifying injury severity [73] and monitoring healing progression [74].

There is a growing body of work on automated algorithms for detection and characterization of bone structures in ultrasound. One study demonstrated assessment of micro-architectural parameters of cortical bone, such as porosity, to determine conditions of osteoporosis [75]. Bone surface segmentation with CNNs has also been proposed in recent studies [76]. One reported real-time bone surface segmentation using a CNN with local and global context to improve robustness [77]. A CNN was also employed for bone segmentation and speed of sound calibration on ultrasound images, followed by registration to CT images [78]. While magnetic resonance imaging (MRI), X-ray, and CT are considered gold standards for MSKI assessment, the combination of ultrasound with AI algorithms can help provide a much more convenient, cost-effective triage tool at or near the point-of-injury.

11.4.2 Overcoming AI Development Challenges

The major challenges in developing AI for ultrasound are collecting data relevant for operational environments and labeling images for algorithm training. AI algorithms are data-driven and generally require lots of example images to learn the target tasks for detection or classification. In the field of medical imaging, and particularly portable ultrasound, the process of acquiring large amounts of labeled images is time-consuming, costly, and requires domain expertise. One way to overcome the need for massive amounts of training samples in the target AI task is to leverage transfer learning with models pretrained on ImageNet [79] or other publicly available datasets. These models have been rigorously trained to recognize features in a wide variety of everyday objects with millions of examples. The well-learned feature representations that are relevant to ultrasound can be extracted and used as starting points for model retraining on new detection or classification tasks. This “fine-tuning” process can be achieved with a smaller dataset than would be required if training from scratch.

Regardless of dataset size, there is still a need for annotating ultrasound imagery with ground truth information that supervised AI algorithms must learn. This process is costly, due to the clinical expertise required, and time-consuming, due to thoroughness needed to minimize risk of error. Active learning techniques for semi-automated labeling are one way to reduce the manual burden [80]. The basic principle is to first train an AI model on a subset of data that has been labeled manually. Once the model is trained to achieved a reasonable level of accuracy, it can be applied to predict annotations on some or all of the remaining unlabeled data. An expert can quickly review examples for correctness or make adjustments as needed. Then, the validated annotations can be used for retraining the algorithm. Through an iterative process, the model gets better and better at automatically labeling data, and the amount of manual adjustment decreases. As an alternative to supervised learning (training with labeled data), there are techniques to extract features from data without external annotations in an unsupervised or self-supervised learning framework [81].

Another challenge particularly pertinent to the ED and prehospital settings is the ability to perform AI inference on-device and in real-time. This requires algorithms to be optimized for accuracy and speed, and tightly integrated with ultrasound devices. Edge AI is an emerging technology advancement that is well suited for overcoming these challenges. Edge AI constitutes low size, weight, and power AI systems that can perform detection or classification locally, with minimum latency, and without the need to be connected to the Internet [82]. The capabilities of edge AI are growing rapidly. Among a number of applications, it has shown great promise in mobile computing [83]. As its infrastructure and framework continue to mature, we expect to see more edge AI-based systems used for the extreme environments covered in this chapter and beyond.

11.5 Conclusion

Throughout this chapter, we discussed a variety of medical conditions and life-threatening complications commonly encountered in two unique extreme environments: the emergency department and prehospital settings. We also discussed how ultrasound can assist with rapid diagnosis, triage, and interventions in these scenarios. Broadly speaking, ultrasound is one of the most versatile imaging modalities in extreme environments and is often the only available imaging tool in prehospital care. The key limiting factors of ultrasound include the high variability and the high degree of training required for image acquisition and interpretation. With the ongoing advances in AI, particularly in the area of ultrasound image analysis, as shown by the example applications presented in this chapter, we expect AI-enhanced ultrasound will continue to increase the level of device automation and enable non-expert users.

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Chapter 12
Firefighter Personnel and Their Activities in Extreme Environments

F. Michael Williams-Bell and Carolyn McGregor AM

12.1 Introduction: Background and Brief History of Firefighting

The occupation of firefighting dates back to 6 A.D., where the first known fire brigade, called the Vigiles, was established by Emperor Caesar Augustus in Rome. The brigade was divided into four main ranks:

1. Uncinarius, who used a hook for removing burning roofs
2. Siphonarius, who operated the water pumps
3. Aquarius, who supplied water to the pumps and organized the water bucket chains
4. Emperor, who acted as the Fire Chief

Initially, the fire brigade was comprised of seven battalions consisting of 560 men, including one Fire Chief, in each [1].

The first volunteer fire department was created in 1736 in Philadelphia by Benjamin Franklin. It was not until 1850 that the USA formed a full-time paid fire service, whereas in other countries professional firefighters were established in France (1810), Scotland (1824), and England (1832). In Canada, the oldest fire station dates back to 1754 in Halifax, Nova Scotia [1]. In Australia, the earliest form

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of Fire Brigade was in the 1820s in the New South Wales colony where a military Brigade of soldiers were trained to use firefighting appliances.

Today, firefighting is a well-established occupation that protects the public from fire disasters, assists with medical emergencies, and leads search and rescue operations. These duties cause firefighting to be one of the most stressful occupations, physically and psychologically, in the world [2–5]. Data from the United States Fire Administration (USFA) reveals between the years of 1977 and 2005, an average of 113 firefighters were killed per year while on-duty, excluding the tragic events of September 11th, 2001 [6]. Between 1998 and 2001, approximately 42% of all firefighter related deaths occurred due to myocardial infarction [7], indicating the immense cardiovascular stress/workload firefighters are exposed to.

12.2 Clothing and Equipment

Firefighters are required to wear personal protective equipment (PPE), which is clothing to protect against extremely high temperatures and reduce the risks to the human body of burns. The PPE is made up of several components including bunker pants, jacket, boots, gloves, flash hood, and helmet. This clothing ensemble completely covers the firefighter's body and protects heat from penetrating into the clothing. It encapsulates the head but also creates a microenvironment impairing heat transfer between the body and the ambient environment and prohibiting adequate heat loss to cool the body [8–11]. The PPE worn increases the physically demanding nature of the occupation [12] but is necessary due to the ambient temperatures reported in the literature, ranging from 38 to 93.3 °C [11–13] and may even exceed 200 °C [14].

Clothing ensembles that include multiple layers absorb part of the radiation in the outer layer and transmit the rest onto the underclothing where it is absorbed and partly reflected. This rebound effect results in heat being stored in various layers within the clothing ensemble. This results in radiation altering the heat loss mechanisms through convection and evaporation and may be affected by the colour of the garment [15].

A self-contained breathing apparatus (SCBA) is worn to protect against toxic contaminants during fire emergencies. The SCBA is made up of an air cylinder, shoulder worn harness to hold the air cylinder, and face mask. The SCBA, typically weighing 10–12 kg, is predominantly situated on the back of the individual.

The total combined weight of the protective clothing and SCBA is approximately 20–27 kg; however, at a typical emergency scene, firefighters will also carry additional tools and equipment that could add an additional 18 kg or more [16, 17]. Some of these additional tools and equipment include:

1. Chains for stabilizing automobiles during auto-extrication tasks (approximately 59 kg)
2. Hydraulic generators (approximately 45 kg)

3. Tool boxes including various equipment stored inside (approximately 13–36 kg)
4. Auto-extrication tools (approximately 18 kg)
5. If the fire is in a high rise, then they will be carrying a high rise pack weighing approximately 18 kg, which may include additional hose lengths

This provides important information that some tools and equipment weigh more than the PPE and SCBA combined, further increasing the metabolic work associated with performing activities utilizing these tools [18] (Fig. 12.1).

12.3 Firefighting Impact on the Human Body

The nature of firefighting has significant impact on the human body. Injuries and fatalities are of extreme concern to firefighters. The risk of injury and the associated direct and indirect workers' compensation costs can be an economic burden to the fire service. Data from the USA reveals that from 2010 to 2014, approximately 30,290 injuries occurred on the fireground. In one year alone (1999), over 45,000 firefighters were injured at a fire scene, with 89% of these injuries occurring while fighting structural fires [23]. In addition, the most common type of injury resulted from overexertion or strain, accounting for 26% of all injuries, followed by 21% due to exposure to the hazard. On-duty injuries to firefighters can be costly, with a reported average of $5000 per worker's compensation claim, with smoke inhalation/asphyxiation costing approximately $1080 [24].

Firefighters must work for prolonged periods of time while breathing through an air cylinder as part of their SCBA that contains a finite amount of air. With the unpredictable nature of fire and other hazardous environments, the risk of injury or fatality resulting from contact to the hazard or smoke inhalation/asphyxia will always be of grave concern (Fig. 12.2). The physiological and psychological impacts are outlined further in the following sections.

12.3.1 Impact on Firefighter's Physiology

One of the first research studies to examine the physical and physiological demands of firefighting was conducted by Lemon and Hermiston [2], who found that the firefighters with a maximal oxygen uptake greater than $40\,\mathrm{mL{\cdot}kg{\cdot}min^{-1}}$ would be able to contribute a greater portion of the oxygen cost through aerobic metabolism compared to those with a maximal oxygen uptake less than $40\,\mathrm{mL{\cdot}kg{\cdot}min^{-1}}$. This study has generated decades of follow-up studies attempting to quantify the impact of firefighting on the human body as well as how individual components of personal protective equipment (PPE), self-contained breathing apparatus (SCBA), and environmental stressors add to the stressful nature of the occupation.

Fig. 12.1 A firefighter performing a hose drag task in a cold environment (−20 °C)

The ability to quantify the physiological demands of firefighting has evolved over the past forty years. In order to evaluate these demands, researchers require the

Fig. 12.2 Firefighters responding to a second story residential fire with an ambient temperature of 7 °C

ability to measure the primary indicators of physical demand: heart rate (HR) and oxygen consumption (VO_2). Furthermore, other physiological characteristics that are important include increased levels of muscular strength and endurance, aerobic and anaerobic power, as well as motor abilities, such as agility, manual dexterity, balance, and flexibility [4].

12.3.1.1 Musculoskeletal System

Firefighters are required to wear standardized clothing and carry a range of equipment that introduce significant stress on the musculoskeletal system. Specifically, their PPE weighs approximately 9.2 kg, and their SCBA weighs approximately 9.5 kg. Depending on the nature of the emergency, they may be required to carry additional equipment ranging from a high rise pack (18 kg) for high rise structural fires [16], cutter and spreader for auto-extrication scenarios (19 kg), as well as a hydraulic generator (45.5 kg). These additional loads place further demands on all physiological components of physical demanding work including the musculoskeletal system.

Initial research by Davis and Santa Maria [19] revealed that HR and VO_2 were increased by 33% while wearing PPE and SCBA during treadmill walking when compared to an equivalent work rate in athletic clothing. Additional research has shown a decrease in work performance of approximately 20% when wearing PPE and SCBA [20, 21]. Two decades later, Louhevaara et al. [22] had participants perform maximal treadmill exercise and determined that maximal work time and walk speed was reduced by 25%, on average. The authors concluded that the decrease in performance was attributed to the extra mass of the PPE and SCBA.

The US Bureau of Labor Statistics estimates that the total incidence of work-related injury in the fire service is 397.5 injuries per 10,000 firefighters. In 2015, the National Fire Protection Agency revealed that the majority of fireground (52.7%) and non-fire ground (58%) operations injuries were classified as sprains, strains, and muscular pains [25]. Firefighters suffer injuries at a rate three times higher than employees in the private sector [26]. Firefighter musculoskeletal injuries are similar to paramilitary and military tactical personnel and include shoulder, lower back, knee, and ankle injuries [27] and are increased by the additional loads that are required to be carried. In terms of injury rates in the literature, a review by Orr et al. [28] revealed that injury rates in an American [30] and Australian [31] population were 177 per 1000 full-time employees. These rates may be underreported with injury incidence rates in other occupations varying greatly from 169.3 (Australian Army) to 240–2500 per 1000 full-time employees (law enforcement) [32]. However, it should be noted that rates of underreported injuries have been observed as high as 49% [33]. The most common sites for injury are the lower extremity and back [27, 30, 34–36], with the back presenting as the leading site of injury, between 20 to 32%, in two studies [27, 34], whereas the lower extremity was similar [35] or higher [30, 36] in other studies. On the contrary, shoulder injuries have been reported to be one of the lowest sites of injury for firefighters [34, 35]. From a cost perspective, Frost et al. [27] reported injuries to the knee were a larger economic burden followed by injuries to the back, confirming that both sites warrant consideration when implementing programs to mitigate injury risk.

Workers' compensation costs are an important factor to consider when discussing injury rates in the fire service. A review by Orr et al. [29] found sprains and strains to be the most common nature of injury [23, 30, 31, 35–41], with an incidence rate ranging from 16% [39] up to 74% [40]. From a budget perspective, the average cost associated with injuries from sprains and strains amounted to a total of $8031 per person [24]. From a mechanism of injury standpoint, slips, trips, and falls as well as bending, lifting, and squatting have been identified as being two of the most prevalent [27, 31, 34–36]. As a result, there is a significant opportunity to propose new approaches for training to build resilience in the musculoskeletal system that enables personal measurement of resilience.

12.3.1.2 Cardiovascular System

During structural and environmental fires, firefighters are required to perform physical tasks such as crawling, walking, climbing ladders, breaching doors and roofs together with carrying or dragging victims. They do this while breathing through their SCBA. During vehicle rescue and other rescue activities, they are required to move and carry equipment in a way that puts strain on the cardiovascular system. The increase in load being carried will increase physiological strain, reduce the individual's work capacity, and increase the risk of injury [28]. In particular, wearing the full PPE results in an increased physiological strain of approximately 35% across several variables, including oxygen consumption, heart rate, minute ventilation, breathing frequency, tidal volume, and rating of perceived exertion. It has been reported that the metabolic impact of the full PPE is approximately 30% of the overall effect, whereas the impact on heart rate was accounted for by 25%, indicating that incorporating equipment modifications can reduce cardiovascular and metabolic costs during locomotion by 25–30%. In terms of the specific impact of the different pieces of the PPE on heart rate, the protective clothing was a significantly greater burden when compared to the protective boots or self-contained breathing apparatus [28].

These activities as well as the acute traumatic risks encountered by firefighters (e.g., burns, smoke inhalation, structural collapse) have significant impact on the cardiovascular system. However, the most prevalent cause of line-of-duty deaths in the fire service are caused by sudden cardiac death, accounting for approximately 45–50% of all firefighter deaths [42]. Specifically, the cardiovascular strain starts with the initiation of the fire alarm signalling an emergency response. The sympathetic nervous system is activated due to the psychological and mental stress from hearing the alarm. The sympathetic nervous activity does not decrease following alarm as the sympathetic arousal at an emergency scene is quite powerful. The alarm response itself has been linked with a five- to sevenfold risk of sudden cardiac events [43, 44]. This increased risk is due to the increase in catecholamines that are released without exposure to the emergency environment and ultimately no immediate requirement for an increase in physical workload. Once the increase in workload commences, the firefighter requires a combination of static muscular contractions and aerobic contribution during activities such as stair climbing, forcible entry, victim search and rescue, and fire suppression [42]. Many of these activities require increased physical demands of the upper body, which can lead to an elevated blood pressure response and increased cardiac workload, increasing the risk of a sudden cardiac event [45].

Initially, measuring HR responses during live firefighting to predict VO_2 [46, 47] or using the Douglas bag method [48] during fire simulation scenarios were the safest and most practical indicators of the physical demands placed upon firefighters. Studies have shown that heart rate can increase between 47 to 61 bpm, from a resting level, within the first minute following a fire alarm [49, 50]. Within the first 5 min of a fire, heart rate can continue to increase up to a level of 195 bpm and maintain a level greater than 160 bpm for 90 min.

Heart rate has been well documented, as it is one of the easiest measures to collect, whereas other cardiac variables highlight the cardiac strain and cardiovascular risk associated with firefighting [42]. After 20 min of firefighting activity, which include three short bouts of strenuous activity, stroke volume was reduced by 35% [51] while a more recent study revealed a reduction of 13% following multiple training evolutions within a 3 h period [52]. Among other changes observed include reductions in left ventricular diastolic size and volume, as well as left ventricular shortening fraction and ejection fraction. Although the specific clinical significance of these cardiac changes is not fully understood, they did occur in apparently healthy firefighters absent of any known cardiovascular disease. The study found decreased left ventricular function and system arterial compliance, suggesting that firefighting may alter arterial–ventricular coupling.

Follow-up studies have attempted to quantify this arterial–ventricular coupling and found that after 3 h of live-fire training, cardiac contractility was reduced by 28% [53], whereas a laboratory study examining the role of heat stress during a 20 min work to rest ratio during treadmill walking in full PPE revealed a 32% increase in wave 2 (early diastolic ventricular function) amplitude [54]. These studies suggest that, following heat stress, an increased afterload on the myocardium may be observed. Further field and lab-based studies have suggested that firefighting activities may result in a mismatch between myocardial oxygen demand and supply, potentially causing ischemia during physically demanding work in the heat.

The potential mechanisms that may trigger a sudden cardiac event result from the cardiovascular strain of firefighter; most firefighters are able to cope with this physiological stress. Firefighters who have an underlying cardiovascular condition will have an increased risk of an event during or following firefighting activities. Risk factors such as smoking, hypertension, diabetes, and old age increase the risk of sudden cardiac death, while previous coronary heart disease diagnosis is associated with the greatest risk. In addition, individual factors related to body mass index reveal that those diagnosed with obesity can increase risk of line-of-duty sudden cardiac death threefold [55].

Other studies have also attempted to determine the average metabolic cost of firefighting while determining a minimum aerobic power. Research examining the average VO_2 of firefighting activities have reported values ranging from 1.9 L/min [56], 26.1 $mL{\cdot}kg{\cdot}min^{-1}$ (2.2 $L{\cdot}min^{-1}$) [2], 30.3 mL/kg/min [57] to 33.9 $mL{\cdot}kg{\cdot}min^{-1}$ (2.75 $L{\cdot}min^{-1}$) [58] with minimum VO_2 peak requirements of 33.5 $mL{\cdot}kg{\cdot}min^{-1}$ [57], 35.6–38.2 $mL{\cdot}kg{\cdot}min^{-1}$ (2.8–3.0 $L{\cdot}min^{-1}$) [56], greater than 40 $mL{\cdot}kg{\cdot}min^{-1}$ [2], 42 $mL{\cdot}kg{\cdot}min^{-1}$ [59], and 45 $mL{\cdot}kg{\cdot}min^{-1}$ [4].

These previous studies have effectively determined the average oxygen consumption required during simulated firefighting tasks, but there are limitations when trying to apply them to the general population. As well, controlling the work rate of critical firefighting tasks does not come without major difficulty. The individual's self-determined pace may result in a variety of work rates and energy expenditures during simulated firefighting tasks. From a sudden cardiac death perspective, low aerobic fitness levels may contribute to an increase risk of line-of-duty death because those who are fit can complete a greater volume of work at an equivalent level of cardiovascular strain or experience reduced strain at the same work intensity [55, 60–62] of their less fit counterparts [42]. Many studies have provided evidence that the firefighting community often are classified as overweight or obese with a concomitant decrease in aerobic fitness [55, 60, 61].

Historically, most research has focused on the increased HR and VO_2 during actual and simulated firefighting scenarios; however, work performance in firefighting also requires a large amount of anaerobic energy expenditure [3, 16, 62]. In most firefighting tasks, anaerobic metabolism is a major contributor possibly accounting for more than 50% of the energy required. Of the four firefighting tasks (aerial ladder climb, victim rescue, hose drag, and ladder raise) examined by Lemon and Hermiston [2], average respiratory exchange ratio (RER) values ranged from 0.97 to 1.07, possibly indicating a high anaerobic component. Furthermore, Gledhill and Jamnik [4] collected blood samples 5 min following completion of a series of firefighting tasks and revealed that peak lactate concentrations were in the range of 6–13 mmol/L. Additionally, Williams-Bell et al. [3] examined the physiological demands of a pre-employment screening test, the Candidate Physical Ability Test (CPAT), and reported average RER values of 1.02 in males and 0.97 in females (the average duration of the circuit was 8 min and 32 s). In another study, stair climbing up to an average height of 20 flights while wearing PPE (9.2 kg), self-contained breathing apparatus (SCBA; 9.5 kg), and carrying a high rise pack (18 kg) revealed an average RER of 1.10 [16]. A subsequent scenario quantifying the physiological demands during a search and rescue simulation on the fifth floor of a high rise building indicated elevated levels of anaerobic metabolism based on an average RER of 1.12. Overall, these previous studies highlight the apparent level of anaerobic metabolism that is required to complete the physically demanding job tasks essential to firefighting performance.

12.3.1.3 Respiratory System

Firefighting puts stress on the respiratory system due to having to breathe using their SCBA and the physically demanding nature of the job. In addition, firefighters practice skip breathing to reduce the volume of air being consumed during a hazardous scenario as well as being exposed to the risk of smoke inhalation/asphyxia.

The SCBA that firefighters are required to wear can impact respiratory function during light and moderate sub-maximal exercise, where expired ventilation has been shown to be reduced with an increased VO_2 at the same work intensity [63–66]. In addition, at heavy exercise, expired minute ventilation was increased from 8.1 to $10.1\,\mathrm{L{\cdot}min^{-1}}$ with a concomitant increase in VO_2 of $0.54\text{–}0.8\,\mathrm{L{\cdot}min^{-1}}$ [63–65]. Tidal volume was decreased while wearing the SCBA during all exercise intensities, indicating that breathing frequency caused the increase in ventilation during heavy exercise. These changes in breathing pattern may be the result of the shoulder harness of the heavy SCBA impairing efficient thoracic motion and preventing the ability to move freely [64].

It is evident that wearing PPE and the use of a SCBA increases the metabolic work rate and alters the respiratory responses to physical activity. The increased work rate has also shown an increase in respiratory exchange ratio (RER) values (ratio of carbon dioxide production to oxygen consumption, typically measured in litres/min), which could indicate a greater role for anaerobic metabolism during firefighting activities. The impact of these responses on firefighters' cognitive performance is important to establish appropriate work guidelines to optimize the health and safety of the occupation as well as civilians living in their community.

Over the past 40 years, many researchers have examined the impact of wearing SCBA on physiological demands and work performance. Initial research by Davis and Santa Maria [19] found that when firefighters wore both their PPE and SCBA, heart rate and oxygen consumption were increased by 33%. In addition, when performing a graded maximal exercise test, firefighters had a 25% decrease in work performance, which was attributed to carrying the extra load of the PPE and SCBA [22]. Following these earlier studies, Dreger et al. [67] utilized a more recent version of the SCBA and determined that maximal oxygen consumption was reduced by 17%. In addition to these findings, Eves et al. [68] quantified the impact of the individual components of the SCBA and found that wearing the full SCBA or just the SCBA regulator reduced maximal oxygen uptake (VO_{2max}) by 15%, whereas wearing the SCBA pack and harness but breathing through a low-resistance two-way valve only impaired VO_{2max} by 5%. A recent study by Windisch et al. [69] revealed that the three greatest influencers on firefighting performance during a simulated job circuit were maximal oxygen uptake, the time exercised below their individual ventilatory threshold, and their mean breathing frequency. Despite the requirement for a firefighter to wear an SCBA during many emergency scenarios, their risk of developing chronic respiratory diseases is well known [70]. In an attempt to combat the deterioration of lung function, the National Fire Protection Agency in the USA has recommended that firefighters perform a spirometry test on a yearly basis [71].

Skip breathing is a technique that firefighters learn to conserve air in their SCBA to enable them to be within the live fire scenario for longer. It involves altering the normal breathing pattern to skip a breath and is achieved through performing a pause in breathing. Techniques such as skip breathing resulting in altered breathing patterns together with elevated breathing due to the physical demands create significant strain for firefighters.

There is a high risk of smoke inhalation/asphyxia for firefighters. Smoke inhalation/asphyxia account for approximately 17% of all firefighter deaths and 84% of fatalities occurring within a structure [7].

12.3.1.4 Thermoregulatory System

The human body requires to balance the processes that induce heat gain and heat loss in order to maintain an internal temperature around 37 °C [72]. If the amount of heat being generated in the body is greater than the avenue for heat loss, body temperature will increase [73]. On the other hand, if heat loss is greater than heat production in the body, body temperature will decrease [74]. The body's metabolic rate provides the necessary energy to perform mechanical work, ultimately resulting in heat generation. Heat is produced within the body due to the metabolic reactions in the body not being 100% efficient, as 70% of energy that is produced is converted to heat and the remaining is released as heat [75, 76]. The mechanisms that provide heat transfer include through conduction, convection, radiation, and evaporation, which when combined with heat generation, result in the level of heat storage (S).

One of the primary physiological responses to heat stress is blood flow redistribution, in particular, a reduction in splanchnic blood flow [77, 78] to provide adequate perfusion of the skin for heat loss [79]. Heat stress has been shown to reduce splanchnic blood flow by approximately 40% with a rise in T core from 37 to 41.5 °C [80] producing cellular hypoxia in the liver and intestine [81]. This severe heat stress can produce intestinal injury leading to splanchnic endotoxemia through intestinal barrier dysfunction, thereby increasing the permeability to endotoxin [80, 82].

Endurance-trained individuals have been shown to tolerate uncompensable heat stress situations reaching $T_{core} \leq 40.0\,^{\circ}\mathrm{C}$ compared to untrained individuals who terminate exercise at T core close to 39.0 °C [83]. One mechanism that may explain the increased heat tolerance in endurance trained individuals is linked to heat shock proteins (HSPs). Untrained individuals have been reported to have elevated plasma endotoxin concentrations following exercise in the heat compared to their endurance-trained counterparts, who maintain gastrointestinal integrity through an increase in HSP 72 and greater resistance to endotoxin [84, 85].

One of the first physiological functions for the role of HSPs discovered was their ability to become resistant to heat stress following heat exposure [86–88]. Although the specific mechanism is not well understood, they appear to play a role in processing stress-denatured proteins, managing stress-induced protein fragments, maintaining structural proteins including actin, a chaperone mechanism to transport cellular proteins across cell membranes, and steroid hormone regulation [88–93]. In general, HSPs inhibit programmed cell death (apoptosis) under conditions of heat stress. In particular, HSP 72 has been shown to improve heat tolerance through cytoprotective effects through intracellular accumulation [94–97]. These cytoprotective effects include reduced incidence of apoptosis [98] and ischemic-reperfusion injury while extracellular HSPs have been associated with mediating immunological functions [99–104].

The multiple clothing layers within the PPE required to be worn by firefighters transfer the sweat produced between fabric layers that are in close contact, resulting in evaporation from these layers away from the skin's surface [105, 106]. This situation reduces the efficiency of the body's cooling process by drawing energy from the environment to evaporate sweat. The firefighter's sweat may become absorbed into the PPE altering its thermal and protective characteristics ultimately affecting heat transfer [107, 108]. Maximal evaporative heat dissipation occurs at the skin's surface when sweat is evaporated and heat is extracted from the skin [109]. Evaporation that occurs away from the skin decreases the efficiency of evaporative heat loss causing the heat of evaporation being extracted from the environment. Furthermore, Havenith et al. [110] demonstrated that when the evaporation site was within clothing layers, the heat of evaporation was significantly lower. The heat requirement was dependent on the distance between the skin and the site of evaporation as well as the number of overlying and underlying layers.

In addition to the thermal insulation of the protective clothing, the additional weight of the PPE increases metabolic heat production [111, 112]. However, the additional weight is not the sole contributor to this increased metabolic rate. Teitlebaum and Goldman investigated the effect of wearing a five-layer clothing ensemble and found that an increase of 16% in metabolic rate could be attributed to the increased friction from the clothing. The friction also affects movement creating a hobbling effect and can be attributed to specific characteristics of the clothing including the weight, fabric, and thickness [12].

The other variable in the heat balance equation that affects the properties of heat exchange is radiation. This type of heat transfer can be absorbed, reflected, and partially transmitted by the clothing materials with dark colours absorbing more heat than lighter colours [113]. The material absorbing the radiant energy increases its temperature and also increases the radiation that is emitted from the material [15]. Nielsen [114] found that 90–125 W could be added to the heat load through exposure to 742 $W{\cdot}m^{-2}$ of additional radiation while wearing dark or light clothing, respectively. The 35 W difference in heat load between the two garments accounted for a 0.1 °C increase in T_{core} and 0.7 °C increase in T_{skin}, which also included 7 $g{\cdot}h^{-1}$ of sweat evaporation. The most important factors affecting the clothing system are the reflection coefficient for radiation of the outer clothing layer and the wind speed [15].

The microenvironment within the PPE is hot and wet reducing the benefits of heat acclimation when encapsulated [111, 115]. Acclimation to a hot and wet environment does not follow the same physiological adaptations to a hot and dry environment, which provides a lower test T core as the main benefit [111–117]. Studies utilizing PPE have shown acclimation to a hot, humid environment reveals greater benefits than in a hot, dry environment [118]. The physiological benefits of heat acclimation while wearing normal athletic clothing do not provide the same benefits when fully encapsulated in protective clothing. Aoyagi et al. [111] showed that pre- and post-heat tolerance times were not changed despite the increased sweat rate (0.14–0.23 $g{\cdot}h^{-1}$) following 8 weeks of aerobic training at 60–80% VO_{2peak} for 30–45 min per day plus 6 days of heat acclimation (45–55% VO_{2peak} for 60 min per day at 40 °C and 30% relative humidity). McLellan and Aoyagi [106] examined the effects of heat acclimation in a hot and dry (40 °C and 30% relative humidity) compared to a hot and wet (40 °C and 30% relative humidity while wearing NBC clothing) environment exercising for 60 min at 45–55% VO_{2peak} for 12 days. The authors found that T_{core} took longer to increase 1.0 °C following the hot and wet acclimation protocol when performing a heat tolerance test in a hot and dry environment (40 °C and 30% relative humidity, wind speed & lt; 0.1 m/s). In addition, increases in the rate of sweat evaporation and tolerance time occurred following acclimation in a hot and wet environment [119]. In these encapsulated clothing conditions, even light or moderate workloads can cause T_{core} to continually rise, known as uncompensable heat stress (UHS), unless the exercise intensity is reduced or stopped and/or the protective clothing ensemble is removed [8, 120, 121]. Heat acclimation in a hot and dry environment would appear to provide different physiological adaptations compared to humid heat conditions [122].

Training status has been shown to improve heat tolerance with trained individuals capable of tolerating $T_{core} \leq 40.0$ °C during UHS compared to untrained sedentary individuals terminating exercise close to 39.0 °C [83]. This increased heat tolerance in trained individuals may be linked to an increase in heat shock protein (HSP)

72 resulting in the maintenance of gastrointestinal integrity [84] and increased resistance to endotoxin [85].

12.3.2 Impact on Firefighter's Psychology

There has been a large volume of research on the physiological responses of wearing PPE while working in the heat. This research has ultimately provided valuable information on the individual factors that impact tolerance in the heat and has led to improved working guidelines for firefighter exposure to increasing temperatures. In addition to the physical limits imposed by working in the heat, it is also important to quantify how these metabolic and environmental conditions may play a role on cognitive function.

There are several cognitive processes that appear to be typically involved in firefighting. These include working memory, sustained attention, reaction time, spatial awareness, and information processing [124, 147]. These aspects of cognition are critical to allow the firefighter to perform job tasks and safely exit the emergency. Firefighting activities require firefighters to remain alert, maintain high levels of mental function, be aware of their surrounding environment, and make split second decisions all while under conditions of extreme heat and psychological stress [123–125]. Heat stress can be life threatening when T core rises above 40 °C. This level of hyperthermia can cause delirium, convulsion, and coma resulting from dysfunction of the central nervous system (CNS) [126]. Firefighting can impose a situation where body mass reductions of 2% can occur in firefighters during simulated victim search and rescue tasks due to profuse sweating [127]. This level of decrease in body mass has been reported to impact cognitive function, specifically mental concentration and working memory [128]. The exact mechanism of this decrease in cognitive function is unclear; however, it may be that firefighters reallocate their attentional resources to cope with the environmental stressors. This reallocation of resources may reduce the individual's capacity to process task-relevant information of the emergency situation [129–133].

Research on the cognitive performance of firefighters working in hot environments is limited; however, the few studies that have measured changes in cognitive performance have utilized mental performance tests such as simple reaction time following simulated firefighting tasks [134–136]. However, simple reaction time is of limited importance in firefighting with more emphasis on decisions being made correctly rather than at the fastest speed possible. Furthermore, simple tasks may not elicit differences between different environmental conditions. In addition, Kivimäki and Lusa [134] reported a decrease in task-focused thinking occurs during simulated smoke-diving resulting from increasing levels of physical stress.

More complex neuropsychological assessment batteries have been implemented in an attempt to overcome the limited applications from simple reaction time assessments. One of these batteries, the Cambridge Automated Neuropsychology Test Automated Battery (CANTAB), was utilized in one such study examining changes in cognitive function during heat exposure in firefighters [127]. The authors reported that there was no change in rapid visual information processing, spatial memory span, and choice reaction time using the CANTAB testing battery following a firefighting simulation. The major limitation in this study was the authors conducted the cognitive performance tests 30 min following the firefighting simulation activity. The authors acknowledged that the effect of the heat exposure may have been lost during the transition period [127].

Radakovic et al. [137] used the CANTAB tests to investigate the effects of exertional heat stress and acclimation on male soldiers exercising at 5.5 km/h in either a cool (20 °C) or hot (40 °C) environment who were randomly selected into:

1. Control group with no acclimation
2. Passive heat acclimation (35 °C, 40% relative humidity) for 3 h over 10 days
3. Active heat acclimation (35 °C, 40% relative humidity) walking for 1 h at 5.5 km/h over 10 days

The participants wore their normal combat uniform with a backpack filled with 20 kg of sand to simulate regular weight burden for a maximal duration of 90 min. Three CANTAB tests were administered to assess cognitive performance: motor screening (MOT), reaction time (RTI), and rapid visual information processing (RVP). The study found that attention performance was lowered in some tasks in the unacclimated soldiers but only in complex tasks (RTI); the simple motor tasks (MOT) were relatively unaffected by heat stress. The authors concluded that exertional heat stress resulted in mild deficits in attention in the unacclimated soldiers and were only significant in complex tasks, whereas simple cognitive tasks were unaffected by the heat stress. Furthermore, Racinais et al. [138] examined the effects of passive hyperthermia on cognitive function in subjects who were exposed for 2 h in 20 °C, 50 °C only, and 50 °C where cold packs were also applied to the participant's head. Cognitive function was assessed using the match to sample (MTS), choice reaction time (CRT), pattern recognition memory (PRM), RVP, and spatial span (SSP) tests of the CANTAB battery. The authors found that passive hyperthermia without cold packs caused significant decrements in both the memory tests (PRM and SSP) when compared to the 20 °C condition, while the more simple attention tests (MTS, CRT, RVP) were not affected by hyperthermia. This may indicate the existence of frontal lobe activity impairments and that the addition of cold packs to the head during the 50 °C passive hyperthermia condition preserved working memory capacity (SSP) but not visual memory (PRM).

Morley et al. [124] examined the effects of heat stress on aspects of cognition (short-term memory, sustain and divided attention, and reaction time) before and after exercise in non-firefighters while wearing PPE. The exercise protocol implemented in this study utilized a work to rest ratio, similar to Selkirk and McLellan [121], with 20 min of exercise at 4.5 km/h followed by 10 min of recovery (consisting of 3 min at 2.5 km/h, 4 min standing rest, and 3 min at 2.5 km/h) in an environmental temperature of 33–35 °C up to a total exercise time of 50 min. In a parallel study, the same protocol was conducted but also included cognitive measurements up to 120 min post-exercise. Participants performed 46 and 48 min of exercise in the two studies with no decrements in neuropsychological testing immediately after exercise; however, recall on a memory test was impaired 60 and 120 min post-exercise.

There are still numerous unanswered questions surrounding the effects of heat exposure on cognitive function in firefighters. It is unclear if the potential decline in cognitive performance during firefighting activities is the result of increased physiological strain or other psychological aspects including heightened anxiety [123]. It is unknown if the number of years a firefighter has on the job would play a beneficial role as the skill level of the individual appears to play a role to combat the negative effects of heat stress [139]. In a review study by Barr et al. [123], future work should focus on performing simulated firefighting tasks in a climatic chamber, replicating actual intensities and durations, while using computer-based cognitive function tests that are more realistic to the mental tasks encountered at emergency scenarios.

12.3.3 Environmental Impact on Firefighters

The nature of firefighting necessitates their exposure to a diverse range of environmental conditions from extreme colds in winter to the heat of a structural or forest fire. As a result, their core body temperature can be significantly impacted.

12.3.3.1 Heat

The nature of firefighting results in exposures to hot environments while working in PPE reducing the ability to lose metabolic heat during firefighting activities [48]. Elevated levels of heat stress do not necessarily follow a linear increase in air temperature, specifically in firefighting where PPE is worn. From the vast literature that has examined the effects of heat stress on exercise tolerance, a review by Cheung et al. [18] identified three main factors that determine an individual's tolerance time during UHS: (1) their initial core temperature, T_{core}, at the start of heat stress trial, (2) the T_{core} that they are able to tolerate before exhaustion, and (3) the rate of increase in T_{core} throughout the duration of the heat stress trial.

These factors illustrate the need for more approaches to provide adequate countermeasures for practical application. In order to reduce the heat gain following heat stress, studies have shown that inducing a drop in T_{core} from 39.5 °C to 37.5 °C in under 10 min can be accomplished by immersing the entire body into cold water at 2 °C [140]. Intermittent (10–20 °C) or continuous (20 °C) water immersion for 15 min during a recovery period can improve work output in a subsequent exercise bout compared to active recovery on a cycle ergometer at 40% VO_{2peak} [141]. However, whole-body immersion during recovery breaks at fire emergencies is troublesome and not overly practical. This has led to more practical applications in the field with research showing that hand and forearm immersion as a countermeasure (Fig. 12.3),

Fig. 12.3 Firefighters participating in active cooling as part of the rehabilitation protocol following a fire suppression and search and rescue scenario in a live fire training simulation (ambient temperature 21 °C, relative humidity 61%)

in 17 °C water, can provide 70% of the ensuing heat loss within the first 10 min of cooling [120]. This protocol is very promising in reducing the physiological strain in hot conditions and is a practical solution on the fireground, but the possibility of reducing cognitive impairments has not been evaluated.

12.3.3.2 Cold

In addition to exposure to the extreme heat of structural and forest fires, firefighters can be required to perform in extreme cold. Automotive extractions and other rescue operations can be required to be performed during harsh winter conditions. However, limited research has been conducted on the physiological effects of performing firefighter job tasks while working in a cold environment (Fig. 12.4). The majority of the literature in this area has been conducted through a military context or focuses on the specifics of the protective clothing material.

When it comes to cold stress while wearing protective clothing, the unique aspect is that the concern for heat stress is still applicable. Individuals wearing PPE while working at a high metabolic rate under conditions of extreme cold weather can still experience heat stress. In addition, during periods of rest or lower metabolic work rate where clothing is wet from sweat or precipitation, a situation where excessive heat loss occurs can be present leading to substantial reductions in core and skin temperature [142, 143]. Furthermore, during cold exposures the biggest concern for

Fig. 12.4 Firefighters performing an auto-extrication in blizzard conditions at an ambient temperature of −20 °C

health and performance may be the temperature in the hands and feet compared to core temperature during heat stress conditions. Overall, the physiological signs and symptoms of cold strain include a decrease in skin temperature, particularly in the arms, hands, legs, and feet, an increase in metabolic rate due to shivering, and a decrease in core temperature [144]. In the past two decades, there has been more focus on understanding the impact of cold exposure on manual dexterity performance and predicting degradation as well as the impact of extremity cooling on lowering brain temperature and core temperature [145–153].

While working in PPE during cold exposure, cold strain can occur if there is insufficient insulation in the PPE or if the evaporation of sweat is reduced, causing wet skin or damp clothing [144]. This limited vapor transfer ultimately reduces the insulative properties of the PPE, increasing the risk of hypothermia during subsequent periods of reduced physical activity or rest. Several injuries can occur due to excessive exposure to cold stress including freezing (when skin temperature falls below freezing) and non-freezing (when the skin remains cold and wet for an extended duration) cold injuries [154]. Eventually, if core temperature decreases below 35 °C because heat loss exceeds heat production, hypothermia will occur.

12.3.4 Impact of Biological Sex and Gender

Firefighting is a traditionally male-dominated occupation. Those who wish to pursue a career in the fire service must be physically and psychologically prepared for the job. Women may experience additional physical and psychological stress simply due to their gender. It is not uncommon for female firefighters to experience self-doubt and have others perceive their performance as inadequate [155]. Although there have been limited studies conducted on the female firefighter population, Chetkovich [156] examined gender and race in an urban fire service and found that females were more likely to enter the occupation with less relevant background and experience self-doubt. In addition, females perceived that they must perform their skills and tasks perfectly as any indication of mistakes tended to be magnified by their colleagues. Although the level of stress experienced by female firefighters appears to be high, Murphy et al. [157] found that males and females were more similar than different on their reported measures of job stress and symptoms of stress. Female firefighters did report higher scores on job skill concerns and discrimination factors. Although total symptom of stress scores were similar, females revealed significantly higher levels of depression. Overall, the study by Murphy et al. [157] reports that both male and female firefighters experience the same amount of stress and symptoms stress, concluding that females can still perform as effective firefighters in their profession.

In terms of the physical stressors of the job, it is thought that a female firefighter has approximately 60% of the strength of the average male firefighter [158]. This particular view is one that is typically cited and held against women looking to enter into this occupation. In order to dismiss the view, the Los Angeles Fire Department developed a strength training program targeted at passing the physical abilities test [159]. The specific exercises included in the program were similar to those used in the test as well as those found on the job. Following implementation of the program, fourteen out of fifteen female candidates passed the physical abilities test compared with two out of eight women who underwent the previous strength conditioning program, which consisted of typical weight training exercises. In general, this study provided evidence that with task-appropriate physical conditioning, women are capable to attain the level of strength and endurance required to pass the physical abilities test [159].

In the twenty-first century, more female recruits are being hired representing approximately 3% of the work force in the USA with gender being an important factor related to the epidemiology and task performance of firefighter [160, 161]. When it comes to performance on physical performance tests, previous research has shown that females demonstrate lower performance scores compared to males [162]. In addition, studies reveal that females consistently differ on cardio-pulmonary, muscular strength and endurance, and firefighting task performance when compared to males [3, 163]. However, additional research needs to be conducted on gender and sex differences in the fire service as it relates to the physiological demands, thermoregulation, cognitive demands, and acclimation.

12.4 Training and Resilience Assessment and Development

12.4.1 Skill Development

Firefighters are required to go through extensive training to obtain the necessary certifications and qualifications to work in the field. Every country, province, and state can have different requirements in order to be eligible for consideration for employment in a fire department. For instance, in the province of Ontario the minimum requirements are:

1. Must be 18 years of age or older
2. Legally entitled to work in Canada
3. Free of criminal convictions for which a pardon has not been granted
4. Possess an Ontario Secondary School Diploma or academic equivalency
5. Ability to work in rotating shifts, including nights, weekends, and holidays
6. Speak, read, and write English fluently and communicate clearly and precisely under demanding, high-pressure situations
7. Have Standard First Aid and CPR level HCP (Health Care Providers) certification

However, fire departments and municipalities within Ontario may further require applicants to have additional credentials, including the Pre-Service Firefighter Education and Training Program Certification from an Ontario College or NFPA 1001 Firefighter I and II certification or several other certifications or previous fire-related employment [164].

The National Fire Protection Association (NFPA), a global self-funded non-profit organization, delivers information on codes and standard to eliminate death, injury, property and economic loss due to fire, electrical, and related hazards. In particular to firefighters, NFPA 1001: Standard for Firefighter Professional Qualifications identifies the minimum job performance requirements for career and volunteer firefighters whose duties are primarily structural in nature. Similarly, NFPA 1051: Standard for Wildland Firefighting Personnel Professional Qualifications identifies the minimum job performance requirements specifically for wildland firefighting personnel. It is within these standards that specific skills must be acquired, evaluated, and passed before an individual can meet the expected requirements to be hired as a firefighter. NFPA 1001 consists of 22 sections covering topics such as forcible entry, ladder practices, fire hose practices, salvage and overhaul, fire streams, and ventilation practices, among others [165]. Fire departments that require these additional credentials and even those that do not will still provide several weeks to months of department-specific training before a firefighter is assigned to a regular crew.

12.4.2 Load Carriage Training

The NFPA 1001 standard does not require specific load carriage training; however, many of the live-fire training prerequisites require an individual to wear their PPE and SCBA while completing the necessary practical components. In terms of candidate testing, the load carriage element is incorporated into the specific job tasks being completed. For instance, as part of the Candidate Physical Abilities Test, which is primarily utilized in Canada and the USA, individuals are required to wear a 50 lbs vest for all 8 job tasks that are to be completed during the timed circuit. In addition, an extra 25 lbs is worn on the shoulders while completing the first task, a 3-min stair climb activity. Another candidate physical abilities test that is used in the province of Ontario is known as the York University Firefighter Test, which consists of 8 job-related tasks that must be completed while wearing a 40 lbs vest and 4 lbs ankle weights. Additionally, the Firefighter Applicant Physical Aptitude Evaluation, developed by the University of Alberta and utilized by fire departments across Canada, requires individuals to wear full PPE and SCBA, weighing 51 lbs, during the aerobic fitness assessment on the treadmill and throughout the 6 job related tests.

12.4.3 Fitness Development

Specific aspects of a firefighter candidate or career firefighter's physical fitness is assessed through one of the various physical abilities tests required prior to being hired by a fire department. However, once hired, mandatory fitness training and yearly fitness assessment is typically not required. The NFPA 1583 standard provides an outline for a fire department's command staff on how to implement physical fitness testing and development. In addition, the International Association of Firefighters (IAFF) has developed the Wellness-Fitness Initiative (WFI) to further emphasize the need for ongoing fitness assessment and development as well as procedures on how to implement this initiative successfully within a fire department. Currently, implementing NFPA 1583 or the IAFF WFI is not mandatory and is up to each individual fire department, in conjunction with the local union, to determine if and how such a fitness assessment and development process is integrated into ongoing or yearly inclusion. As seen throughout this chapter, it is evident that all components of physical fitness (i.e., aerobic capacity, body composition, muscular strength, muscular endurance, and flexibility) are important to not only achieve optimal health outcomes but also improve firefighting performance and ultimately reduce the risk of injury or fatality.

12.4.4 Resilience Assessment and Development

Resilience is defined as “the ability to adapt and successfully cope with acute or chronic adversity” [167]. Firefighters can be exposed to traumatic events, including but not limited to recovery of a deceased body, witnessing a colleague become trapped, and are also exposed to the various occupational stressors at an emergency scene. These exposures can lead to the development of post-traumatic stress injury (PTSI) symptoms. The ability to assess and ultimately improve resilience can decrease the severity of those symptoms. Resilience provides a buffering effect by protecting against the adverse effects of PTSI [175]. Currently, there is little research on resilience assessment in the firefighter population. In the military population, there have been efforts to improve resilience through stress inoculation training (SIT) and relaxation breathing techniques, which will ultimately enhance the coping mechanism associated with deployment-related stressors and reduce the incidence of PTSI [166].

The majority of resilience-related research focuses on self-reported questionnaires and surveys to quantify the individual’s level of resilience. For instance, the Connor–Davidson resilience scale (CD-RISC) is a self-rated questionnaire considered useful to measure the ability to cope with stress among individuals with or without PTSI. A higher score on the CD-RISC indicates better resilience, whereas a higher score on the Stress Vulnerability Scale (SVS), a measure of perceived distress, infers an inability to be resilient [167]. Although this approach can provide some meaningful insight, an objective and quantifiable model that can be deployed, in real-time, during an emergency would prove beneficial for Incident Commanders’ decision-making and resource allocation. A study by Winslow et al. [168] measured the effects of stress and resilience on military training tasks by testing performance output through physiological changes in HR and skin conductance level. The authors determined that short-term resilience and cortisol levels are predictors of stress but the effectiveness of this technique still needs to be further evaluated.

Similarly, the Pre-deployment PTSI Checklist-Military Version (PCL) used in the Warriors Achieving Resilience (WAR) study confirms that reduced heart rate variability (HRV) among soldiers in conjunction with higher scores on the PCL is related to poor autonomic regulation directly linked to a higher risk of developing post-deployment PTSI symptoms [169]. Pre-deployment training can reduce post-deployment PTSI symptoms in a cohort of experienced soldiers; however, the majority of current tools include self-reported measures with additional work required to develop a more comprehensive process for resilience training [170].

The link between resilience and the development of PTSI symptoms has been shown in firefighters. Using several self-reported measures (Life Event Checklist, Perceived Stress Scale, Occupational Stress Scale, Impact of Event Scale-Revised, and Connor–Davidson Resilience Scale), Lee et al. [171] determined that firefighters with resilience scores in the 10th or 25th percentile were protected from the direct and indirect impact of traumatic stress. As with much of the literature on firefighters, this study only included a small number of females, which provides uncertainty as to whether the overall findings can be generalized to the female firefighting population. In addition, the use of self-reported measures in the field may not be a practical solution to assist in the decision-making efforts of Incident Commanders.

To provide a more objective approach to resilience, a physiological correlate would be beneficial, but the specific pathways linking resilience and health are not well understood [172]. In order to determine the physiological mechanisms that may be linked to resilience, Walker et al. [173] identified heart rate variability, cardiovascular recovery, dehydroepiandrosterone (DHEA), and the immune system, among others, as promising candidates.

PTSI has been consistently linked to lower HRV suggesting autonomic inflexibility, which could be due to sympathetic overactivity or parasympathetic insufficiency. Some evidence has shown that diminished HRV immediately following a traumatic event may be linked to the development of PTSI [177]. In addition, several studies have shown an association between lower HRV and PTSI, potentially resulting from an inflexibility of the autonomic nervous system [174–179]. In a study examining the association between pre-deployment HRV with risk of PTSI, Minassian et al. [180] suggested that HRV may not be related to incremental changes in the severity of PTSI symptoms but may play a role in the development of the syndrome and its negative consequences. In addition, a low HRV may be considered an at-risk state in comparison to an individual trait.

12.5 Health Monitoring During Active Duty

Due to the physically demanding nature of firefighting, the physiological (cardiovascular, respiratory, thermoregulatory, muscular) and psychological demands are extremely high during an emergency scenario (Fig. 12.5). Although firefighters are ultimately in charge of their own personal work limits, Incident Commanders at an emergency are tasked with deploying their resources (i.e., fire crews) in a manner to optimally reduce the impending threat. In order to maximize their resources, Incident Commanders would benefit from a greater understanding of the limitations of their firefighters. To date, fire services and Incident Commanders typically rely on information relating to the amount of oxygen remaining in an SCBA air cylinder to determine when a firefighter is to be removed from a fire or toxic environment. In addition, firefighters may be limited to a pre-determined number of air cylinders or total amount of time at an emergency to determine the duration of their active duty at a scene. These standard operating procedures, though based on several decades of information and experience, are blanket protocols intended to cover and promote safety for all firefighters. If an individualized tracking and information system existed, this could provide Incident Commanders with the ability to optimize their resources, improve performance and productivity, and ultimately reduce the risk of injuries and fatalities. From a practical standpoint, the variables that could be utilized by an Incident Commander include heart rate, heart rate variability, respiratory rate, expired ventilation, oxygen consumption, skin temperature, and

Fig. 12.5 Firefighters perform a fire suppression training activity at an ambient temperature of 21 °C and relative humidity of 61%

core temperature. Currently, all of these physiological variables can be collected, measured, and analysed in a research laboratory or in a controlled field setting, but their capacity at a real-life emergency have been limited. Currently, the technology exists in the form of biometric wearable devices; however, these particular devices may not be rated for exposure in an extreme environment, such as firefighting, or may be too costly to be considered for implementation as part of an individual firefighter's PPE. Despite these limitations, the technology does exist and with further advancements could, theoretically, be integrated into the typical PPE and SCBA worn by firefighters.

12.6 Application to Other Domains

Although firefighting is a unique occupation requiring near-maximal effort and exposure to traumatic events, there are several other domains that would benefit from enhanced understanding of the physiological, psychological, and cognitive demands of the profession. Several other industries require increased protective equipment and uniforms that increase overall body weight, including police, military, paramedics, and correctional officers. The specific job tasks that are required to be performed by individuals might vary between occupations, and the underlying physiological and psychological implications have tremendous overlap. All of these personnel must perform their duties in an ever-changing environment providing further indication that a more comprehensive understanding and ability to monitor the health of these individuals is critical in order to optimize performance and reduce the risk of injuries.

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Chapter 13
The Extreme Environments of Elite Sports

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13.1 Introduction

The world of elite sports seems to be a cosmos in its own—an extreme one—but how is the term "elite sports" defined, and what makes it an extreme environment? The answer to both questions is highly dependent on the individual's perspective. This chapter seeks to provide answers to these questions. It is about offering perspectives on the world of elite sports as an extreme environment. It is not about an irrevocable truth, but rather about giving a starting point for critical thinking, hypothesize, and deriving educated ideas.

An overview and possible definitions of elite sports environments are present, as well as a discussion of physical and psychological circumstances, which can drive

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the environment to be an extreme one, extreme in the sense of challenging human homeostasis and allostasis on different levels.

13.1.1 What Is Elite Sports?

The term “elite sports” is commonly used today, and however, there is neither in the daily language nor in the scientific world, a sharp definition of the term. This is shown in a meta-analysis from [27]. The authors found eight different operationalizations of “elite” or “expert” in sport science research. Both terms are generally used interchangeably. The operationalization differs from “being no novice,” over “doing a specific sport over a longer period of time,” to “world class athletes.” Furthermore, the lingual inaccuracy goes on with the term “sport.” We can think about the disciplines of e-sports, motorsports, or chess. That is why we start by discussing several perspectives on what “sport” in general and “elite sports” in particular can mean [25, 26].

13.1.1.1 Definition of Sport

“Sports” can stand for a lot of different activities, and by just considering Olympic sports, it becomes obvious what large bandwidth of sports exists. In simplest terms, sport is about movement—of the body, the mind, or some vehicle.

Hodges et al. distinguished four unique features of the general term sport. These features address the movement, abilities developed, time constraints, and differing roles [19].

Movement

Movement can be composed of one single movement chain, like archery, and locomotive movements, like running, or requires a sequence of complex movements, like gymnastics or ballet. In this case, the dichotomy of interactive and coactive is used. While interactive sports like handball, soccer, and basketball yield high dynamics and interactions between the individual athletes, coactive sports like archery or bowling can be performed independently by one individual at a time.

Moreover, sports can be classified as single, double, or team sports. Considering this categorization, the type of interaction is not clearly defined. In case of gymnastic team competitions, athletes cannot actively influence the performance of a teammate, which is different to interactive sports like basketball or doubles in tennis or badminton [34, 35].

Especially, in team sports, participants can have different roles, like the drummer and the rowers in rowing. Roles can differ in relation to scope of rules, which apply for them, like the goalkeeper in ice hockey or the quarterback in football. Different roles could be defined by different tasks and movements, like setters and receivers in volleyball. Thus, different roles in team sport require a different set of skills [38].

Abilities and Skills

Another distinguishing feature in sport is the different physical and mental abilities/skills required to perform the sport. On a physical level, it can be divided into strength, endurance, speed, and mobility, with every sport requiring a unique combination of all components [36].

Psychological skills can be divided into cognitive-perceptual, emotional, communication, and motivational. As it will be shown later in this chapter, these skills are interdependent and influenced, as well as influencing the physical parameters. This interplay becomes obvious in the complex physio-psychological process, which underlies acquiring and performing sport-specific technical skills. For example, there are so-called slow-paced introspective games like golf and archery, which rely more on improvement through trials and automations. On the other side of the spectrum, fast-paced interceptive games like tennis or handball challenge an athlete by the high complexity and individuality of each action decision [37] and rely more on implicit learning [37].

Time Constraints

Time constraints address an athlete's choice of reacting, dependent on the movement or behavior of the opponent, object or environment. Therefore, not only the application skills itself are relevant but also the time available for decision-making and execution of the chosen action. The time interval for an action can further be divided into the reaction and movement time of the athlete. Thereby, the reaction time describes the decision-making process and is the bases for the actual movement phase. This definition begins with the initiation of the movement and lasts until the completion of the respective motor task.

Further Definitions

Another definition for "sport" stems from the global association of international sports federations (GAISF), which is the umbrella organization for all international sport federations. GAISF's definition is categorized in the following terms:

- The sport proposed should include an element of competition.
- The sport should not rely on any element of "luck," specifically integrated into the sport.
- The sport should not be judged to pose an undue risk to the health and safety of its athletes or participants.

- The sport proposed should in no way be harmful to any living creature.
- The sport proposed should not rely on equipment that is provided by a single supplier.

Furthermore, GAISF uses five categories for its member federation's sports, many of which fall into more than one category:

- Primarily physical (e.g., rugby or athletics)
- Primarily mind (e.g., chess or go)
- Primarily motorized (e.g., Formula One or powerboating)
- Primarily coordination (e.g., billiards)
- Primarily animal-supported (e.g., equestrianism, horse racing)

However, it should not end with these categories for sport. Many more considerations are valid and can be categorized by:

- Movement patterns: single, locomotive, and complex
- Grade of interaction
- Individual, double, and team sports
- Grade of physical, psychological, and technical impact
- Competitive vs. non-competitive
- Indoor vs. outdoor

13.1.1.2 Definition of Elite in the World of Sport

Now, that it became more understandable what the scope of "sport" is, the question arises what is significant about "elite" sport? There are the sport's categories of health, fun, extreme, professional, etc., which carry the core definition in the term itself. Taking this starting point, "elite" means "a selected group that is superior in terms of ability or qualities to the rest of a group or society."[1]

This refers closely to one of the two perspectives of defining "elite" sports—the normative and descriptive perspective. These approaches define elite sport as the ability to constantly demonstrate superior athletic performance. This superiority is relevant for the physiological, psychological, and technical domain [6]. One weakness of this definition is that it strongly depends on the considered sample. Someone who just knows the rules and basic skills of a sport might be called elite to people who do not know the sport at all.

Another approach was to investigate how someone could gain mastery in his or her field, which means acquiring all the technical, physiological, and psychological skills of a domain. The dominant figure in this line of research is Anders Ericsson, who was cited [213] that to his research, that someone needs approximately ten years with approximately 10,000 hours of deliberate practice to achieve mastery. Deliberate practice is thereby the definition of Ericsson as a purposeful and

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[1] https://www.oxfordlearnersdictionaries.com/definition/american_english/elite.

systematic kind of practice, guided by an experienced teacher [213]. It is important to note that Ericsson himself never saw this number as decisive or easily transferable to other domains than music. He even argues that domains like elite sports are not structured in the same way as music and therefore are in need for own definitions and constructs of special practices [213].

When comparing the two perspectives, a primary interest is to focus on the dynamic. The normative approach is quite static and by this only valid for a fixed period. The mastery perspective on the other hand is dynamic. It is not meant that if you accomplished your 10,000 hours, you are finished. It says that at least 10,000 hours are required to enter the realm of experts. From that point on, you must continue to push further to stay elite or even find new ways to surpass the current elite by breaking old limits (records) and setting new ones. Due to that constant search, the environment of elite sports became very dynamic, because there is always someone trying to find a better way of doing things than the current state. In respect of the great dynamic of every elite sport environment, the characteristics of the elite sports also have great influence on everyone who is trying to enter the world class in any field of sport [40, 44].

Considering the two approaches, the following question can be dissected, in order to analyze the ideas behind the perspectives:

“Is a 15-year-old girl, who is the star in her national soccer team elite or not?”

The normative approach could see her as elite to her age group. However, it is not likely that she already accomplished over 10,000 hours of deliberate practice. She could have accomplished this number if she started at the age of four or five, having approximately 2.8 hours of deliberate practice every day of every year since then. An example of one person who might have had these amounts of training from an even earlier age is Tiger Woods. As known, he was already a child a protégé in the sport of golf. On the contrary, Roger Federer practiced a multitude of ball sports in his childhood and did not specialize in tennis until his middle teenage years. When he started focusing on tennis, his “competitors” had already invested a decade of deliberate practice regarding tennis [39].

Taking both the normative perspective and the development process into account, we can define the elite sports environment as

“The top competitions in each sport and the training process with the purpose to compete/succeed in this competition.”

The term “top competition” thereby refers to the highest competition level possible in each sport, with examples being the Olympic Games, world championships, and world series. Especially, for team sports, national leagues like the NBA or IPL, as well as international club series, such as the Champions League in Europe, are often seen as the top competitions. These events and competitions, where athletes can qualify for the top competitions, are also influenced by the elite world. However, the longer the way to the main competition, the more the influence of some characteristics of the elite sport decrease (e.g., organizational stress, public attention, time investment).

The training process can also be assessed using two perspectives. First, there is training to become elite, which normally starts in childhood or youth and is focused on developing promising talents to perform in the elite world. Therefore, this part is also highly influenced by the elite sports world. On the other hand, there is the rhythmic training cycle in preparation for the top competition. The entire training process is thereby highly tailored to the characteristics and challenges of the individual sport.

13.2 Characteristics and Challenges for Elite Sports as an Extreme Environment

The previous sections provided information on how the elite sports environment and the accompanying training process are defined. Now, the characteristics and challenges for these environments are investigated.

Elite sports carries the following characteristics:

- Highly competitive
- Performance on point
- Search for perfect “fitness”
- Human body as main “performance-tool”
- High investment of energy and time
- Dealing with injuries
- Global phenomena and public attention
- High amounts of money for only few at the top
- Constant feedback and support

13.2.1 The Characteristics

13.2.1.1 Competition

The elite sport world is all about becoming and remaining the best in your sport or becoming the best you can be. Both ideas can influence each other. By becoming the best version of yourself, you can become the number one in the world or you may not. However, if you strive to become the number one, that could push you toward your personal and internal limits. It can hold you back to fulfill your full potential, as just 80% might always be enough. In the end, you will not know how much and which of your potentials you would have evolved to, if you are not driving on full account. Life is no experiment with a control group. Hence, the question arises: “How to assess your performance (development)?” It can be broken down to whether an athlete measures himself/herself against others (normative) or against the athlete’s past self (ipsative). The number one assessment in the elite sports world, however, is always competition.

The origin of the word competition stems from the Latin word, *competere*, which means “strive in common, strive after something in company with or together.” Competition itself can be defined as “an event or contest in which people take part in order to establish superiority or supremacy in a particular area.”[2] In elite sports, competitions always have a clear set of rules and try to guarantee the highest possible grade of fairness and safety. It is important to acknowledge that most of the elite sports competitions have become mega-events, which take place in huge stadiums and draw a lot of media attention [45, 46]. Overall, the interpretation of competition can be coming together to strive after optimal performance in the company of like-minded people.

13.2.1.2 Performance in Elite Sports

The overall goal of elite sports is to deliver the best possible performance at the top competition—not before or after. Hence, it is always about striving for optimal “fitness” in competition. Thereby, fitness not merely reflects “being strong and healthy (or) suitable to fulfill a particular role or task.” Fitness in the elite sports environment means to be specifically adapted on a physical and psychological level to deliver optimal performance in competition. Often, it is necessary to resist allostatic needs, like keeping the pace and not slowing down in the race, or act against all primal instincts like attacking a gap in the defense in handball or basketball, knowing it will hurt, when the athlete gets hit by an opponent.

Optimal performance can be defined by the amount of efficient actions during competition, where non-action can be the most efficient as well. It is important to state that part of every (non)action is a conscious or unconscious decision-making process [47, 48].

13.2.1.3 Optimal Decision-Action

The optimization of sport-specific decision-making–executing processes is one of the key components of elite sports fitness [32]. Decision-making is an obvious factor in combat and game sports [49], but it is also relevant for all other sports, such as endurance or racing sports [50, 51]. The term “decision-acting” should be introduced in this context and represents the entity of decision-making process and execution of the action. Moreover, it has to be considered that a decision-action cannot be separated from the environment in which it happens. Hence, optimal decision-action is always situational. Factors that can define the situation are the environment [49], opponents, personal skill sets, and inner state [52].

In soccer for example, if an athlete gets the ball in front of a goal, the first thing that is important is to be clear which goal you are in front of. Further important

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[2] https://www.lexico.com/definition/competition.

factors are, what the score is and how long you have played as well as how exhausted and confident you are. The quality of ball-handling skills against one or more opponents, as well as pass accuracy, might have an impact on athletes' decision.

In the end, every decision-action could be defined by four interconnected phases: perceive, process, predict, and perform/act. All four phases influence one another and interact on parallel streams. Perception can come from the exterior via vision, hearing, smell, and spacial awareness or from the interior like the position of the body as well as feeling [53]. All exterior and interior information is constantly processed by the athlete, updated, and compared to mental models in the memory to predict the next state of the environment and act accordingly [41, 49]. The main focus of the action can be directed at the external or the internal environment—e.g., hitting an opponent after an argument or calming yourself down.

Another important factor regarding optimal decision-action is the ability to get "in the zone" or "flow" as it is called by Csikszentmihalyi [13, 14, 27]. Flow is thereby defined as "... state of optimal experience arising from intense involvement in an activity that is enjoyable, such as playing a sport, [...]. Flow arises when one's skills are fully utilized yet equal to the demands of the task, intrinsic motivation is at a peak, one loses self-consciousness and temporal awareness, and one has a sense of total control, effortlessness, and complete concentration on the immediate situation (the here and now)" [42].

Considering the flow perspective, the perfect fitness is if the athlete's ability is exactly matched by the challenges of the competition and decision-actions happens without conscious effort. That means that it is so challenging that is proved to give all he has and on the other hand not too challenging to overstrain the athletes' systems.

13.2.1.4 Optimal Fitness in Elite Sports

Being in elite sports means to constantly search for new ways to become fitter, which implies better adaptation to the given competitive environment. As every sport has its unique rhythm, as well as physical and psychological requirements, it differs from sport to sport what "fitness" in particular means. For a sprinter, it could be about 2–3 races at top speed at the Olympic Games, for ball teams the entire road to the final of a tournament, and for a martial artist that one fight for the title of world champion. It is about being optimally fit at the right moment. Therefore, elite sports often seems to be about that one chance in a lifetime, athletes are preparing for.

To get the chance and prepare for it, elite athletes make huge sacrifices and invest a lot of their time, energy, and sometimes health [32]. Moreover, there are longer training periods, where athletes are constantly pushing their bodies out of a homeostatic state and forcing it to adapt to new challenges, both physically and mentally.

Unfortunately, due to the constant pushing toward new limits, the occurrence of injuries is a normal part in an athlete's career [43, 54]. Injuries are one of the most significant threats to the longevity of elite athletes and, when an injury ends the career of the industry's star prematurely, this can pose a significant threat to the business of sports. Continued growth of the sports market has resulted in increasing commercial opportunities and, inevitably, greater physical demands on the athletes to play harder, faster, and longer. There is a lot of money at stake, but it is only available for those few who perform and succeed at the top level. Therefore, preventing, coping with, and returning back from injury is another important part of elite sports and the pursue of optimal fitness.

13.2.1.5 Environmental Factors

Being an elite sports athlete is not simply about optimal adaption in respect to competition but also to all accompanying environmental factors around the competition. As a global phenomenon, competitions take place all over the world or at least all across a country, e.g., pro leagues like the NBA in America or IPL in India. There are also plans to take some games to different continents. Thus, athletes have to travel a lot for competition and therefore have to be able to adapt to new surroundings, climate, and time zones. This includes accommodation, training and competition environment, nutrition possibilities, as well as safety issues, and sometimes even special political situations.

There are a few days "off," providing a short period of real free time in between training, traveling, competition, and active regeneration. Furthermore, there is the issue of financial support [55]. Taking part in the elite sports world is not cheap. Associations, clubs, and single athletes invest, besides their time and energy, a lot of money. Often only the top of the top can get back what they invested. One example is the world long distance triathlon world championship in Hawaii, the Iron Man. Just to get to the starting line, an athlete has to invest at least 10,000 Eures.[3] If the athlete finishes in the top ten of the competition, he starts to earn money. Otherwise, the athlete will remain on its costs. This is why sponsoring is a massive topic in the world of elite sports [56, 57]. It is estimated that over 48 billion US Dollars will be spent on sport sponsoring in 2021.[4] However, being sponsored adds additional duties and stress to an athlete's already packed schedule.

13.2.1.6 Social Factors

Elite athletes are always under observation, while performing and often even during their training and in their private life. Part of being an elite performer is to get constant feedback, whether wanted and forced upon you. During the performance, there is usually a large crowd of thousands of people watching, cheering, or "booing." Not to mention the millions on the televisions and social media channels.

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[3] https://rued.com/ironman/kosten-teilnahme-ironman.

[4] https://www.alistdaily.com/lifestyle/advertiser-spend-sports-sponsorship-warc-study/.

Due to this high public awareness, elite athletes are not just athletes, they can become viable marketing tools and social influencers. Consequently, almost every elite athlete has their own social media channels and is sponsored as part of a company's marketing strategy. On the contrary, due to the abovementioned time, training, and traveling, time for close relationships is spare.

However, an elite athlete is barely alone with all the previously mentioned challenges but surrounded and advised by a multidisciplinary staff of experts [58]. Staff size can vary from one trainer to a whole team. The staff size and variety of professional backgrounds can support or interfere with each other [58]. Working with and improving the quality and effectiveness of the team around the athlete/team becomes more and more important in the elite sports world. It is about communication and coordination of the different expertises, building up synergies and avoiding interference effects. Some coaches became even more famous than many athletes they coach, such as Vince Lombardi (NFL, Green Bay Packers), Phil Jackson (NBA, Chicago Bulls and Los Angeles Laker), and Jürgen Klopp (Bundesliga, Borussia Dortmund and, Premier League, Liverpool FC). Consequently, it is possible to make a remarkable carrier in elite sports as part of coaching staff, rather than being an athlete.

Elite sports does not happen in a social vacuum, even if sometimes it seems like it is own universe. There are four social spheres. The inner private one including the athlete, their spouse, friends, siblings, or parents. The training group or team sphere, which includes athletes of the same team and supporting staff. Then there is the competition sphere where different athletes and staff meet and compete. Lastly, there is the public sphere, which consists of all media, sponsors, and fans.

13.2.2 The Challenges

The new introduced characteristics of elite sports environment impose multiple challenges to an athlete on different levels including:

1. Sport-specific challenges:
    - Constantly pushing limits without crashing the system
    - Structure and coordination of the training process to be at one's best at the main competition
    - Be in the optimal state of body and mind at the main competition
    - Being mentally resilient in competition and in high demanding training phases
    - Performing complex psychomotoric tasks under high physical strain
    - Extreme dedication—their entire life is adapted to the profession (e.g., biorhythmus, nutrition, place of living, etc.)
    - Handling injuries

2. Environmental challenges:
    - Adapting to new climate and time zones
    - Keeping a balanced and constant diet
    - Finding good sleep
    - Handling financial matters
3. Social challenges:
    - Staying focused and intrinsic motivated through all extrinsic temptations and distractions
    - Dealing with expectations
    - Handling fame and public criticism
    - Working with different characters
    - Building deep relationships
    - Finding privacy and time for one's own

13.2.2.1 Mastering Stress

All challenges accumulate to one important coping strategy, to mastering stress. The correct amount of stress is needed to adapt and perform. Too much stress, however, can harm the performance [54, 81] and the athlete itself in short but especially in the long term [59, 60]. It is important to realize that stress is not merely due to physical load training. It is the accumulated impact of an individual's reaction to physical, psychological, and social stressors, which need to be considered [30, 59, 64].

Three Definitions of Stress in Elite Sports

To approach a common understanding of the term stress, three influential definitions are presented:

1. Sleye, 1997 [77]: "... a state of threatened homeostasis, which is reestablished by a complex repertoire of physiologic and behavioral adaptive responses of the organism. The adaptive responses may be inadequate for the reestablishment of homeostasis or excessive and prolonged..."
2. Del Giudice, 2018 [4]: "... stress occurs when a [...] control system detects a failure to control a fitness-critical variable."
3. Folkmann, Lazarus, 1984[62]: stress (or distress) is experienced by an individual when the perceived demands of a situation exceed the perceived available resources to meet these demands.

Consequently, stress is always a complex bio-psychological process/reaction with strong interactions and interdependencies of biological subsystems which are influenced by the subjective evaluation of the situation.

13.3 Impact on the Human Body and Mind

As we have identified, the main challenge of the elite sports environment is mastering a multitude of different stressors, and we will look more closely at what these stressors are. Stressors are all intrinsic and extrinsic adverse forces that challenge homeostasis [61].

13.3.1 Stressors

It is important to note that stressors are a constant and important part of the life process. We will look in particular on the effects of elite sports environment's stressors on the human body and mind.

First of all, it is very important to recognize that all physical and mental systems that are included in the human reaction to stress have evolved over thousands of years. Hence, the origin and purpose have been to preserve and promote life. It was not about running a mile under four minutes, and it was about running faster and longer than the prey or the predator. It was about strolling around and exploring, it was about escaping danger, it was about fighting, and it was about social acceptance and support [17, 62, 63]. The main concern of the body is how and where to save and invest energy, inside the body and over time, always pursuing the overall goals of survival and reproduction.

In elite sports, a lot of energy is spent without acute threat to survival or chance to reproduce. Often within elite sports, athletes push limits so far that it is much more about threating and not ensuring survival. This raises the questions about competition and hard training. Why should the body "waste" so much energy and what are the short- and long-term consequences on the human body and mind system (BMS)?

13.3.1.1 Intrinsic and Extrinsic Stressors

The distinction of "intrinsic" and "extrinsic" is different, whether it refers to the individuum or the task. Referring to the individuum, intrinsic stressors arise from spontaneous physical and mental activity, whereas extrinsic stressors are generated by reactions to external stimuli like the environment (e.g., temperature, noise, etc.) or other people (e.g., social pressure) [1]. Another branch of literature investigated if stressors are intrinsic/task-contingent or extrinsic/peripheral to the task at hand [2].

13.3.2 Dynamic Stress Regulation

As Seley (1959) stated, stress occurs when homeostasis is threatened. Homeostasis in the realm of elite sports is defined as “any self-regulating process by which biological systems tend to maintain stability while adjusting to conditions that are optimal for survival. If homeostasis is successful, life continues; if unsuccessful, disaster or death ensues. The stability attained is actually a dynamic equilibrium, in which continuous change occurs yet relatively uniform conditions prevail.”[5]

In regard to the dynamic aspect of homeostasis, the model of allostasis was introduced. Allostasis translates to “maintaining stability (or homeostasis) through change” [65]. Allostasis is about maintaining the state of dynamic balance in changing environments over time. Through this response, the biological systems adapt to emerging or anticipated internal or external changes. In doing so, allostatic responses often trade short-term benefits for long-term costs. The sum of all allostatic responses is called allostatic load [4]. The respective scope model by Romero et al. [3] could be the most comprehensible stress-adaptation models for application in elite sports. It introduces four main concepts:

1. Predictive homeostasis: anticipatory changes due to circadian rhythms and experience (e.g., the night before competition)
2. Reactive homeostasis: temporary changes due to unpredictable events (during competition)
3. Homeostatic overload: excretion of the normal (critical point in competition)
4. Homeostatic failure: state that is not compatible with long- or short-term health (over-training, injury)

Allostatic responses tend to have immediate benefits and long-term costs. Rising levels of physiological mediators such as glucocorticoids increase energy availability to deal with present challenges, but deplete the individual’s reserves and may result in tissue damages, particularly if exposure to stress is severe and/or chronic [66].

13.3.3 Short-Term and Long-Term Adaptation

Considering the impact on the human BMS, it is important to be aware of possible short- and long-term effects. Short-term refers to a training session or competition, whereas long-term effects are about adapting over a longer period to the elite sports environment.

The impact on the human BMS is sport-specific, as it is the main purpose of the athlete to impact and alter their fitness for a specific competition. The following

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[5] https://www.britannica.com/science/homeostasis.

section will describe the general impacts and BMS's reactions to competition, and the long-term effects, combined with possible risk factors for both.

13.3.3.1 Short-Term Effects

Fundamentally, the impacts of elite sports on the BMS, which can be seen as mere information for the BMS are the result from forced stress on the body systems. Due to the interdependence of the subsystems, in bodily reactions, the entire BMS is involved, although in some sports only demand actions of a specific body part or due to environmental changes, such as temperature or altitude. The BMS's subsystems that are impacted by the stress reaction following the trigger of elite sports competition can be divided into nervous endocrine, metabolic, cardiovascular, respiratory, digestive, temperature regulation, sensory, and psychological systems.

These systems are all interacting together like an orchestra and thereby creating a person's individual stress response. At the beginning, there are several stressors, which are common to all elite sports. These are the ones connected to organizational stress [55], public attention [70], travel and accommodation [67, 68], motivation/arousal [69], and general physical activity. Furthermore, each sport competition impacts the BMS through specific stressors. Within one sport, this could be due to different locations and climate changes.

13.3.3.2 Short-Term Adaptation During Competition

An example would be two different types of triathlon. The most popular triathlon, the Iron Man, takes place in Hawaii with water temperatures of 26 °C, atmospheric temperatures of 28–38 °C, and air humidity of approximately 90%, while the Alaska Man triathlon is performed at water temperatures about 13 °C and atmospheric temperatures between 10 and 18 °C. Same sport activities, however very different environmental challenges, especially impacting the temperature regulation system.

It is obvious that different sports trigger the BMS in different states and conditions. Powerlifters, race drivers, and marathon runners are subjected to significantly differing stressors. Thus, it is important to obtain an overview of the stressors common in competition.

Every competition can be divided into three phases: the preparation phase, the performance phase, and the post-performance phase. The duration of the different subphases is highly dependent on the sport, organization (series vs. time event), and the location where it takes place. Each phase can further be divided into subphases.

The preparation phase purpose is to produce optimal fitness for competition. It consists of the training, the anticipatory (can start up to several weeks to hours before the performance phase), acclimatization, and the warm-up and "ready-to-go" phase.

The performance phase is the period where the actual competition takes place and full performance has to be delivered by the athlete. It depends on the sport how the performance is structured, but in general there is a clear start and finish, which can be more or less externally (100-meter race, team sport games, etc.), or self-determined (gliding, lifting, gymnastics, etc.), as well as including open phases in between.

The post-performance phase contains reflecting about and recovering from the performance. Dependent on the competition mode, this cycle can be repeated one or multiple times. For example, in long-distance racing (swimming, running), the cycle only takes place once, and in team sports, there are half, third, or quarter times that can serve as one cycle, as well as each game during a tournament. In many track and field athletic events, the athletes have to perform several rounds like in jumping, powerlifting, or throwing disciplines. Hence, when thinking about elite sports competition, it is also important to take the structure of performance delivery into account, especially in the scope of dealing with stressors and recovery. A half time break in football should have restorative effects, and therefore the BMS should come to rest; however, the entire system has to regain action mode as soon as the second half starts again. The same is true for sports where two or more games/fights/heats are performed in on day or over several days.

13.3.3.3 Phases of Competition

As stated, it comes down to balancing and using stress in the right way. This is why the considerations take the nervous system as a starting point, because there the general stress response of the BMS is orchestrated.

The most obvious stressor is the physical activity itself. Additionally, the psychological side of the competitive situation becomes a stressor. A combination of both, the degree of physical (in-)activity and mental process, starts multiple systemic reactions to cope with the homeostasis threatening stressors. These reactions are caused by anticipated or acute increased energy and oxygen demand in the muscles and brain [71]. Physical activity can be defined as all body movements that increase energy use beyond resting levels and is usually distinguished by its proportional demand on specific muscles and the overall aerobic capacity. It is important to state that there is no load on a muscle without aerobic load and vice versa.

13.3.3.4 Pre-competition Phase

Not to be neglected in the pre-competition phase is travel and acclimatization. How long and intense these parts are dependent on the time, structure, and location of the competition. Especially, long-distance travel with uncomfortable posture and little space to move as well as extreme changes in time zone or climate, like temperature [22], air humidity, or air pressure can become influential stressors to the elite athlete [16, 55]. Often this has an impact on sleep and/or the recovery status of athletes [31] and their metabolism [22].

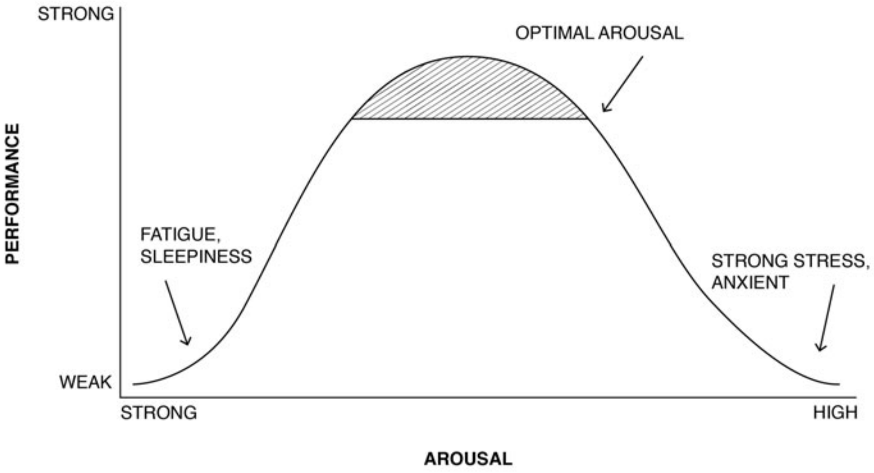

Fig. 13.1 The task-specific arousal level for optimal performance lies in an individual corridor between high tension and extreme looseness

Stress has the function to act as information for the body and is often "translated" by the autonomic nervous system and the endocrine system. This is why, prior to competition, an anticipatory response of the autonomic nervous system kicks in, in order to prepare the BMS for the challenge of competition ahead. The nervous system increases heart rate and contraction power and blood flow to the muscles. This can start to occur several days prior to the actual competition and mostly remains until close to the start of the competition. The timing of the anticipatory response is crucial for optimal performance, because the BMS should be in an optimal state of arousal for the competition [23, 27]. The correct arousal means the optimal balance of the sympathetic and parasympathetic nervous systems. Normally, for competition, a domination of sympathetic activation is wanted, because it boosts the metabolism and prepares the cardiovascular sensory system for action. It is important to note that an "optimal" range is highly individual and dependent on the sport or even within different phases of one competition, Fig. 13.1. Therefore, an inappropriate anticipatory response can either delay the onset of the right arousal state or on the other hand waste energy because stress is eminent over a longer period of time. That could, for example, impair sleep before a competition.

The entire process can be triggered by motivational aspects of looking forward to or being nervous about the competition [12, 129] or by specific competition-related cues such as the few of the stadium or hearing the crowd. The motivational response depends on the athlete's perspective on the competition. It is seen as chance to gain something or as some kind of threat? The wanting system including its main component, dopamine, activates the motivational part of the system if it anticipates future rewards. To tap into the dopamine-driven system, curiosity, and a feeling of voluntary action and positive challenge seems to be helpful. On the other hand, if competition is seen more as a threat, the BMS might be more activated through noradrenaline, adrenaline, and cortisol. It could be that the more dopamine in the fore-run, the more opioids in the aftermath.

One standardized building block in athletes pre-competition routine is the so-called “warming up,” with the intention to prepare the whole BMS for attainment of optimal performance. It can include active and passive parts. It can be aimed at different parts of the BMS, e.g., rising metabolism, activating neuromuscular pathways, or cognitive patterns. Besides the activation and preparation of the BMS, this phase is also used to take advantage of the post-activation potentiation, a phenomenon that leads to higher performance due to prior activity [7, 19, 24]. It is highly recommended to specify the pre-competition routine to the needs of the individual athlete and sort in respect to the current external and internal circumstances [21]. Often the physical preparation is succeeded by a transition phase to the start of the competition, which is most often characterized by keeping our building up the optimal level of arousal through mental strategies (meditation, self-affirmation, focus [15]) or simple physical (e.g., breathing, tapping, shaking) strategies. It is often accompanied by music to amplify desired effects [9, 28].

13.3.3.5 Performance Phase

The performance phase is as unique as every sport, not to say as every single competition. Nonetheless, there are some factors that all performance phases have in common. There is a special kind of tension and focus right before the beginning, independent of the control over the starting point. Normally, there is raised sympathetic activity which increases alertness. As stated before, the subjective appraisal of the situation might determine whether the arousal is based on dopamine circuits indicating the motivation to win or the adrenaline/cortisol axis and by that the fear to lose. Once the competition has started, every athlete wants to reach as fast as possible into his or her “zone,” the phenomenon often referred to as flow and stay there as long as possible [13, 14, 27]. Being in flow is reached when the whole BMS of the athlete is entirely challenged and the athlete is able to keep adapting in states of reactive homeostasis. After that often a phase of homeostatic overload can occur. During the overload, the body is not able to keep a stable homeostatic state. This is regularly accompanied by discomfort, pain, and fatigue. From this point onward, top performance becomes a mental game.

There are many discussions that fatigue is more like a feeling or emotion than a physical phenomenon. The body holds energy reserves which it normally holds back for survival or survival-near situations. At this stage, the “mind” has to convince body to move on.

There could be two different strategies to progress through the “mind-stage”:

- One possible way to get pass this could be creating another strong burst of dopamine and opioids through a strong goal focus and bringing to mind what rewards will wait.

- Push through it “on cortisol and noradrenaline” fight or flight level until opioids kick in for the survival modus.

If neither of these strategies work or the competition goes on for too long, the athlete is at high risk of injury or total breakdown. This is one reason why the use of performance enhancing drugs and pain killers can be very dangerous to the athletes’ health. Although this topic is highly important and complex on its own, it would be beyond the scope of this chapter and thus will not be further discussed. If the athlete is able to push through, he gets into a state where opioids let him overcome fatigue and/or pain and get back into his/her “zone.” On a chemical level, it could be that a dopamine strategy leads to a higher release in opioids and consequently into the production of more nitrogen monoxide, which supports recovery and mediates the onset of the relaxation response [10, 20].

13.3.3.6 Post-performance Phase

After the performance, there is an immediate emotional evaluation, followed by a cognitive appraisal. Besides the psychological process of evaluation, learning, and closure, there is the physical process of recovery. The post-performance phase is mainly about evaluation and starting the recovery process. Both processes can thereby influence each other in both supporting and suppressing ways [135]. Normally, there is an almost instant internal assessment of failure or success. The outcome of this evaluation is related to the motivation and expectations prior and during the competition [18]. Relating to the previously mentioned dopamine driven “wanting/gaining” motivation in comparison to the fight/flight driven “not losing/surviving” something, success could either be having won or not lost. Evaluating the competition as success might lead to a faster switch into parasympathetic activation and consequently faster recovery [29, 98]. On the other hand, the feeling of having failed could keep up stress and sympathetic activity and hence hinder recovery processes. Self-compassion can help reduce the negative effects of felt failure [8].

Furthermore, a mental exertion could lead to the skipping of post exercise/competition actions to boost recovery, because they would demand mental effort. Skipping recovery measures could also be caused by an overly euphoric state, because the athlete does not feel the momentary need due to the opioids. Thus, self-awareness and self-regulation are important parts in the post-performance phase to start mental and physical recovery processes after the competition to be ready for the next competition or training cycle. The same holds true for intensive training sessions [135]. Recovery itself is an important part of the training process, which is why it will be discussed in the next section.

13.4 Training

Success, or at least good performance, at competitions is about the complex dynamic of providing the BMS' systems sufficient load and stress to provoke supercompensation and therefore a more adapted level of homeostasis. When performance in competition is the peak of the mountain, training is the entire way up and down of this mountain. Yes, coming down is thereby equally important as getting up. To stay in this picture, if you want to conquer another mountain, first of all you have to go back down into the valley and then consider to restart climbing.

The main objective of elite sports training is to enable future peak performance in competition, not once, but recurring, because being elite is about constant improvement and staying at the top for a period of time. When considering about top stars in elite sports in the likes of Roger Federer, Serena Williams, Tiger Woods, Megan Rapinoe, Kobe Bryant, Aly Raisman, Cristiano Ronaldo, Michael Phelps, Lindsey Vonn, Usain Bold, Lewis Hamilton, or Wilma Rudolph, one can realize that they did not stop after their first peak. They continued to push further, not just individually, but for the whole of the sport. To accomplish something like this, it is not enough to just pushing oneself as hard as possible. Training in elite sports is also about taking time to recover and performing preventive work to sustain the BMS. It is also about learning how to deal with the challenges of being on the read and being a person of public interest.

13.4.1 Perspectives on Training Processes

There are two main perspectives on the training process, the mechanic and holistic training process. The "classic" or mechanic approach is about the special disciplines. Imagine it as different Lego stones which are used to build up optimal fitness for one sport. The complex is built by adding and connecting separate parts.

On the other hand, training can come from a holistic perspective, starting by observing the complex and trying to understand it by breaking it down. The complex is the fitness during competition. The mechanic approach is like building a house or machine, while the holistic approach is more organic like observing a living creature in nature.

Even so in the holistic approach, they are not clearly separated, we could distinguish three big parts in the training process: physical, mental, and technical skills. As stated before, the main purpose of the training process is to provoke adaptation in the direction of increased competitive fitness in the interplay of these areas. There is a large amount of literature dealing with the different training approaches on varying levels of specification to different systems and sports. Hence, this section is about some key principles of the training process, as well as some possible fruitful future directions.

Additionally, in the holistic approach, they are not clearly separated. We can distinguish three big parts in the training process: physical, mental, and technique.

13.4.1.1 Adaptation in the Training Process

Stress is the indicator for adaptation. Consequently, the training process is about focused utilization of stress. As important as to stress the system to nudge adaptation processes, it is to give time to adapt without being stressed. Thus, at its core, the training process is about the optimal rhythmatizing of the right doses of stress per system with the right amount of time to adapt [121]. While doing so, it is important to keep in mind possible effects of interference or synergy between the systems. For example, the training for speed and endurance can hinder or boost each other [72, 74, 93]. That is why short- and long-term periodization plays an important role in elite sport training [73, 76].

Humans today exist only because they learned to deal with stress, to adapt to it, and to overcome it. The human species is an adaptation machine. The view must move away from two isolated/opposing states (e.g., complete recovery vs. complete fatigue, full stores vs. depleted stores, etc.), toward an understanding of considering physiological (adaptive) processes more as a continuum between two poles. In this process, the body is always trying to create a balance. However, it always remains an unstable equilibrium, an actual "resting point," or the scale is reached if then only for a very short time. So it is more a flowing process than a state. It moves cyclically within an individual range around the point of balance. This range can be seen as a kind of (homeostatic) comfort zone. Adaptation occurs outside this zone, i.e., the edges of this area form physiological and psychological stimulus thresholds. With increasing training experience, this zone expands, and consequently a shift of the physiological stimulus thresholds occurs. In order to provoke an adaptation, a supra-threshold stimulus is required. However, if the stimulus threshold is exceeded too far, there is a risk of an overtraining situation, which in extreme cases can lead to permanent negative damage to the athlete. On the other hand, it can become a challenge for high-performance athletes to permanently set a supra-threshold adaptation stimulus. Thus, there is a risk of a performance plateau, so there is an individual narrow space, a "sweet spot," between overtraining and optimal performance gain per invested resources (e.g., training minutes).

One of the oldest and most common models to explain this complex process is the idea stated by Seyle [64] of the general adaptation syndrome, see Fig. 13.2, which provides a simplified mechanistic but powerful explanation for the relationship of stress, adaptation, and exertion. Furthermore, the model has evolved and has been critically discussed over the last 75 years, and it is still one of the most influential frameworks for training periodization and control to this date [78, 79].

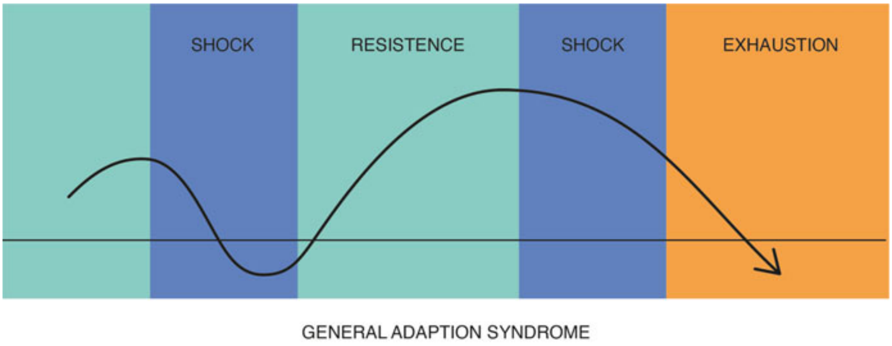

Fig. 13.2 Shock: (training) stimulus pushes the BMS out of homeostasis. Resistance: the BMS super compensates if enough resources are available. Exhaustion: if the next shock is too early or the BMS runs out of resources overtraining and prolonged fatigue can result

13.4.1.2 Training Process for Resilience

A word that is often used in the context of performance and other areas is resilience. Athletes must be resilient and have to build up resilience.

The concept of resilience has got popular in the context of elite sports [5]. Some researchers even state that resilience is a prerequisite for success in elite sport. Even so, or because of that, resilience could be an important construct for elite athletes' training. However, there is a big difference in comparison to other contexts. Athletes often put themselves in challenging, high stress situations on purpose to improve their fitness and performance [5]. Moreover, the science community agrees that the construct of resilience is domain-specific and should therefore only be considered in relation to the context [5]. An ongoing limitation of the extant resilience research is the notably few studies exploring how athletes develop resilience.

In modern "positive" psychology, it refers to the ability of resisting or bouncing back from adversity/crises, due to inner and social resources. An athlete could profit from two kinds of resilience: mental resilience during training to endure and overcome hardship and unease, which is sometimes needed to adapt, because in general the training process does not want the BMS just to "bounce back" but to overshoot and establish homeostasis on a new level. The other part is to aim for what could be called resilience in competition. The ability to recover from unexpected events and adversity during competition and therefore keep the BMS stable to deliver performance.

Team resilience that can be defined as " a dynamic, psychosocial process which protects a group of individuals from the potential negative effect of the stressors they collectively encounter" [75] becomes more and more important [84], not only in team sports but in sports in general, because in the world of elite sport there are no single athletes anymore. Every athlete has at least a small team supporting them. The main characteristics that seem to determine resilience on a team level are group structure, mastery approaches, social capital, and collective efficacy [75]. Morgan and colleagues [85] identified five categories due to which active team resilience development is possible:

- Inspiring, motivating, and challenging team members to achieve performance excellence
- Developing a team regulatory system based on ownership and responsibility
- Cultivating a team identity and togetherness based on a selfless culture
- Exposing the team to challenging training and unexpected/difficult situations
- Promoting enjoyment and keeping a positive outlook during stressors

As shown, the concept of resilience, if adapted correctly to the specific context, can have positive influence in the world of elite sport. On a larger scale, post-stress growth could be interesting phenomena, especially in regard to dealing with injury [33].

Due to the fact that resilience seems not completely fitting for the training process in elite sports, a more suitable concept in the world of elite sports is introduced: antifragility [82], which can be applied on biological [80] and psychological [81] processes.

13.4.1.3 Antifragility for Training Process

Better suited for the context of elite sports is the term "antifragility," which Nassim Taleb [83] introduced to the terms fragile, resilient, and robust, each of the terms describing a "systems" reaction to stress. Where fragile systems break, robust systems persist, and resilient ones deform and bounce back, antifragile systems grow under the impact of stressors.

The elite sports world needs stress for two reasons: finding optimal arousal/stress level for performance and arousal/stress as a trigger for adaptation. The training process should trigger adaptation for improving fitness for competition (GRA: General Adaption Syndrome). All other stressors should be eliminated or reduced. Because that is not possible, it is also part of the mental and physical training process to build up resources to cope with none adaptional stressors [132] as well as increasing work capacity (GRA: work capacity). Work capacity can be defined as "... the ability to tolerate a (raining-)/workload and recover from that workload." [11]. Increased work capacity speeds up the adaptation process, because an individual can endure more intense load in shorter intervals. For example, a sprinter must be able to do a given amount of high-speed running to improve his speed. Therefore, the antifragility of an athlete could be influenced by his/her work capacity [11] and coping mechanisms [86], hence the ability to thrive under adverse circumstances.

13.4.1.4 Assessment in the Training Process

Using the right kind of assessment is a crucial part of the training process, because it gives information about the status quo and development of the adaptation process [36, 87, 94, 124]. Generally, assessment means "the act of judging or deciding the amount, value, quality. or importance of something."[6] The most important parameters for controlling the training process are level of fitness/skill and recovery/fatigue status [112, 113]. Fitness tests can for example assess endurance [88, 90, 91] or strength [89, 92]. Skill tests are often about specific motor skills [93, 95] or on a psychological level like decision-making [96, 97]. Very interesting are combined forms of the assessment.

There is a variety of recovery indicators that are in use but still controversially discussed. Markers commonly used are heart rate for training control [101, 123] and heart rate variability (HRV) for general regeneration state [98–100]. Another method is to assess blood markers like creatine kinase [102–104], cortisol, testosterone, or the cortisol-testosterone ratio [105–109], as well as immune markers [110, 111].

Besides all the so-called objective data, the subjective feeling and reflection of the athlete and stuff are important and valuable parameters [115]. Examples for practical tools are the rating of perceived exertion [138], the Short Recovery and Stress Scale [141], the Profile of Mood States [139], and the Recovery-Stress Questionnaire for Athletes [124].

In particular, during the performance phase of competition, athletes have to rely on their self-awareness, when pushing boundaries or trying to stay in flow [27]. Additionally, the use of wearable tracking devices has increased [120]. During training periods, the individual self-assessment remains an important component of the training control process [112, 114]. Therefore, it is important to train athletes' self-awareness as well as self-reflection as well as to decide when best to apply behavioral or self-report measures [116].

Effective assessment is a vital part of the training because it helps to decide and prioritize what the next steps will be. There are many studies that claim and significantly show that method A or B will help an athlete to become fitter. Time, and especially work or stress capacity, is such a crucial resource, and it is important to prioritize and coordinate training input and sufficient recovery time to generate optimal output [117].

13.4.1.5 Recovery in the Training Process

Giving the BMS time to adapt or recover is a crucial part in the training process [126]. Most of the times, both terms "recovery" and "adaptation" are used together without any further distinction. Recovery is often an umbrella term, which can

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[6] https://dictionary.cambridge.org/de/worterbuch/englisch/assessment.

be defined as a “ multifaceted (e.g., physiological and psychological) restorative process relative to time” [126]. Therefore, adaptation is about finding a better fit to internal and external challenges, whereas recovery is about getting back to a past state of fitness. It could be that the chronic application of short-time recovery measures blunts long-term adaptation [126]. It is not always necessary to rest all bodily subsystems. Often some systems can recover or adapt, while others remain active and under stress.

There is even the possibility of active regeneration, but nonetheless it is always important to have the overall load and therefore adaptation capacity in mind—both physically and mentally. For example, stress in their private life or strain from a journey can also impact the overall stress-recovery balance, by putting extra load on the system or hindering recovery processes and thereby increasing the risk of overtraining [124]. Therefore, it is crucial to see recovery as an active part of the training process, which has to be planned and does not happen on its own [118, 119, 121].

The most important “action” for recovery is sleep [16, 31, 121], whereby the elite sport environment can have a dictating impact on the quality and quantity of sleep [16, 130]. For an optimal recovery, it is not just about the amount but also the quality and rhythmic of the sleep (Fig. 13.3).

Besides sleep, nutrition plays a vital role in the training and recovery process [122, 125, 136]. Curiously, the line between the correct dose of supplementing, medication, and doping is quite thin [Suzic].

Further measures for recovery are [118]:

- Water immersion [131]
- Foam rolling [128, 132]
- Massages [127]
- Compression garments [129]
- Cryotherapy [133]
- Stretching [134]

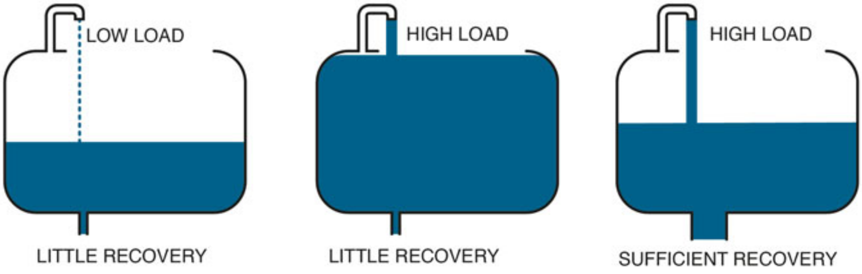

Fig. 13.3 For optimal adaption, the body needs sufficient load. The greater the work capacity (basin) and ability to recover (drain) the more load (water) can be tolerated

Besides the physiological part, the psychological part of recovery is equally important. Effective well-established short-term mental recovery strategies can be applied during training sessions or competition [137, 140]. Different relaxation techniques are one of the most dominant mental recovery strategies [142, 143]. Apart from that, the cognitive and emotional processing of training and competition plays a huge role in recovery processes due to the impact on parasympathetic activities [144, 152].

Due to the importance of recovery, more scientific evidence for these measures and their interplay is needed [31, 118, 140].

13.4.1.6 Improving in Training

The process of improving during training is very specific to every single sport. That is why this section briefly covers some important concepts. If we start the training process from the fitness to competition path, the focus is to improve four aspects of action-decision:

- Quality: effectiveness and efficiency
- Frequency: refractory period to the next day
- Persistence: keeping up quality and frequency
- Adaptability: adjust to circumstances

As there are very specific requirements of skill and physics, there are some overall important mental topics to all elite sports. It is important to note that this list is not all-encompassing, and there are many other ways to structure the domain of psychology in sport. To keep it simple, there are the three fundamental abilities which should be improved:

- **Self-standards:** “Self standards are preferential self-beliefs [...] which consist of self-imposed criteria for judging oneself” [215]. This refers to the ability to set goals and choose values to direct one’s behavior.
- **(Self-) awareness:** “Self-awareness represents the capacity of becoming the object of one’s own attention. In this state one [...] identifies, processes, and stores information about the self.” [214]. To be able to change or adapt immediately or in long-term, an athlete needs to have information about their current state of being.
- **Self-control:** can be seen as all voluntary and involuntary processes and actions that steer one toward a desired end-state [216].

Hence, it is important for every athlete to be able to set meaningful goals [217] and define their own values, have optimal awareness about the processes inside their body and mind as well as their environment, and be able to direct their attention, thought, and emotions as well as their actions in service of their goals and values.

13.4.1.7 Is Elite Sports Healthy?

The main goal of the training process is to conquer new levels of fitness and performance. Often it is not clear what the long-term effects of such intense challenges for the BMS are and if a career in elite sports is a healthy pursuit mentally [149] and physically [145, 146]. It is clear that athletes suffer from mental disorders like anxiety, depression, eating disorders, or substance abuse [153–155], and it seems obvious that the huge amount of stressors in the elite sport environment could have negative impacts on mental health [160] if not handled constructively, especially during times of poor performance or injury [158, 159]. Mental health is defined by the World Health Organization as "a state of well-being in which every individual realizes their own potential can cope with the normal stresses of life, can work productively and fruitfully, and is able to make a contribution to their community. " [156]. One important part of this definition about "normal stresses of life" seems important for the elite sports world, because as mentioned, besides the normal life stressors, an athlete faces voluntarily and involuntarily extreme stressors during training and competition. Therefore, current research and methods have to be applied specifically to the context of elite sports, or otherwise there is the risk of under- or overestimating mental issues [149]. One problem in the elite sports world is some barriers of seeking and getting help for mental problems, such as lack of time and knowledge, as well as negative past experience [159]. But the biggest barrier seems to be the still existing stigmata around mental health in general and in relation to sport [189], because the public and the elite sports environment opinion is that an elite athlete's most important trait is to be "mentally tough" [152, 164, 165], which seems to be the opposite of having mental problems [147]. Therefore, creating opportunities for information about and easy access to mental support is crucial.

Physically, athletes are often seen as "super humans" and many parts of an athlete's lifestyle (e.g., physical activity, health nutrition, little to zero alcohol) support health and longevity [148]. Furthermore, elite athletes seem to have a longer life span compared to the general population [157]. However, the picture is ambivalent if we look at Olympic participants form different countries [171–174]. One very interesting study has shown that the lifespan of US Olympic silver medal winners is significantly shorter than that of gold and bronze winners [175]. This might be a hint at how important the personal evaluation of the competition outcome is. Moreover, there is little research about the quality of life in the afterlife of elite sports. While the athlete's career injury is a permanent threat [178], which has to be managed and prevented [166, 168], long-term effects are still unclear due to a lack of research [161, 167]. A main component about injury is to deal with pain, as dealing with pain is a constant challenge during training and competition [176, 177]. Especially, in the early stage of an athlete's career, injury can have physical and psychological consequences [170]. The recovery process can be supported through [169]:

- Clear pathway to the medical team
- Recognizing identity loss involve the injured athletes with the rest of the teammates
- Educate athletes about how to interpret pain signals

Therefore, it is quite important to bring more attention to the long-term effects and prevention of negative consequences in the elite sport environment [177]. Furthermore, develop a perspective that looks at functional vs. dysfunctional during different times of the career (development, peak, post) [150, 151], rather than a general normal vs. pathological point of view [149], and develop sport-specific interventions [162], taking into account the role of social media [163].

13.5 Discussion

13.5.1 Future Directions

There are a variety of possible future directions in the world of elite sports, of which many will be specific to the given sport environment. Therefore, we will provide an overview of three general trends in the elite sports world: mindfulness, extended reality, and biomedical and brain signals.

13.5.1.1 Mindfulness in Elite Sport

Mindfulness has long found its way into the practice of elite sports. One of the most prominent and successful examples might be the most successful NBA coach Phil Jackson, who won elven championships with the Chicago Bulls with Michael Jordan and with the Los Angels Lakers with Kobe Bryant [179]. Mindfulness is often referred to as “the awareness that arises from paying attention, on purpose, in the present moment and non-judgmentally” [192].

There are several different definitions of mindfulness. Two distinct features that are important to the elite sport world are, firstly, attention to and awareness of present-moment experience and, secondly, acceptance of naturally fluctuating moment-to-moment experiences [193]. This kind of awareness can be applied to everyday activities as well as the execution of sport skills [180], dealing with pain and injury [181–183], reduce stress or heightened awareness and emotional control [184]. Mindfulness can be trained in systematic ways [184], and if cultivated over a longer period of time, mindfulness seems to have multiple positive impacts on elite sport athletes [188]:

- Improve performance [185]
- Increased self-confidence and decreased anxiety [186]
- Sleep quality [187]

- Support for getting into the flow [190, 197]
- Decrease risk of injury [191]
- Dealing with stress [195]

Despite this promising outlook, the high-quality research on the effects of mindfulness in the elite sports environment is still needed [193] and the active discussion between experienced experts from the field of mindfulness and elite sports to bring forward new forms of intervention and investigate possible effects on team levels [196, 197]. Especially, the combination of both mindfulness and bio-/neurofeedback training might be a promising path to follow [194].

13.5.1.2 Technology in Training

Two branches of technology gain more and more importance in the elite sport environment: bio- and neurosignals [152, 198–200, 204] and extended reality [201–203].

Due to the development of modern sensory technology, it is now possible to use wearable and stationary gadgets for the assessment and improvement of the training process [84, 194], as well as for performance enhancement [211]. Heart rate variability and neurofeedback are promising for enhancing psychological skills of focus and self-regulation [84, 206, 211]. Another new critical emerging topic is neuro-stimulation, which comes together with the discussion about its ethics and if it has to be regarded as doping or not [205].

Extended realities like augmented or virtual realities can be used in ways to assess or train skills in a controlled, but highly realistic environment, with the possibility to adapt complexity and challenge levels on an individual but standardized protocol. Furthermore, these realities can be used while traveling or during rehabilitation [210]. Particularly, for complex decision-making training in combination with spatial awareness, these technologies prove to be promising [201, 207]. The technologies can also be applied to enhance recovery processes [212]. Of great interest can also be the combination of both, bio- and neurosensing technology and augmented or virtual reality [200, 208], to utilize possible synergy effects [209].

13.6 Conclusion

This chapter has given different perspectives on the elite sport world as an extreme environment. It became clear that every sport has very unique requirements. The overall purpose of elite sports is to handle and use stress to attain optimal fitness to perform at one's best under the conditions of the highest competition. Due to the fact that elite sport is a global phenomenon with immense public attention and money invested, we have noticed that being part of the elite sport environment opposes an individual with much more challenges than only the ones inherent to the specific sport. Therefore, the elite sports environment can be seen as a sandbox for human development and thriving, always pushing limits further. It can be a driver for new technology and inspiration to millions of people, but it is important to keep in mind the downsides, and "extremes" of this environment, when drawing conclusions from it or establishing new ideas into it. One thing that is becoming more obvious in the endeavor of elite sports is that we cannot separate the mind and the body anymore, perhaps even note the mind, the body, and the environment. Athletes as humans are body-mind-systems in constant dynamic interaction with their environment, and it is important to take that into account when thinking about extraordinary performance and the preparation for it. Last but not least, it is important to note that nowadays none of the incredible performances in elite sports are the deed of one individual alone. Elite athletes can achieve the magnificent things they are achieving because they trust in people to support them in almost every part of their life. Thus, future research and efforts in the realm of elite sports can focus, besides high-end technology solutions, on the utterly human and social components of performance and achievement, overcoming borders and strengthening human connections.

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Chapter 14
Extended Realities (XRs): How Immersive Technologies Influence Assessment and Training for Extreme Environments

Markus Wirth, Wolfgang Mehringer, Stefan Gradl, and Bjoern M. Eskofier

14.1 Introduction

The rise of the third generation of immersive technology hardware and its improvement in usability and wearability was the prerequisite for sophisticated concepts and implementations of immersive systems in various application areas. Innovation-driven industry branches with great popularity like media and entertainment, manufacturing, education, or healthcare have drawn major attention to immersive virtual environments (e.g. PokemonGo,[1] BeatSaber[2], or TiltBrush[3]). In medicine, it is a promising medium for diagnostics [76], surgical support [66], and therapeutics or assessment [25]. In industry and education, it is applied to conduct interactive training courses or for the development of new pedagogical concepts [58, 74]. Further examples of successful applications are to be found in tourism [27], gaming [57], and manufacturing [13].

Technological development further enables to increase immersion and experienced presence of users in virtual environments (VE) by producing devices capable to display stereoscopic content like a wide field of view (FOV) head-mounted

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[1] https://pokemongolive.com/

[2] https://beatsaber.com/

[3] https://www.tiltbrush.com/

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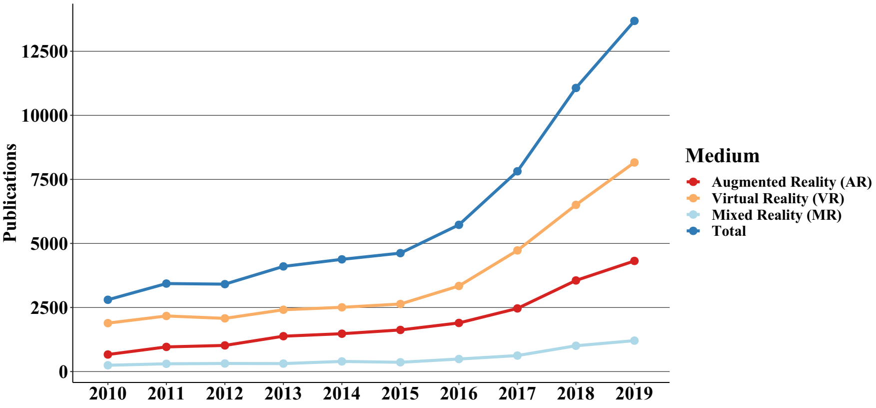

Fig. 14.1 Development of publications regarding augmented (AR), virtual (VR), and mixed (MR) reality between 2010 and 2019. These results are based on the analysis of four scientific databases (i.e. PubMed, Google Scholar, ACM Digital Library, and IEEE Xplore)

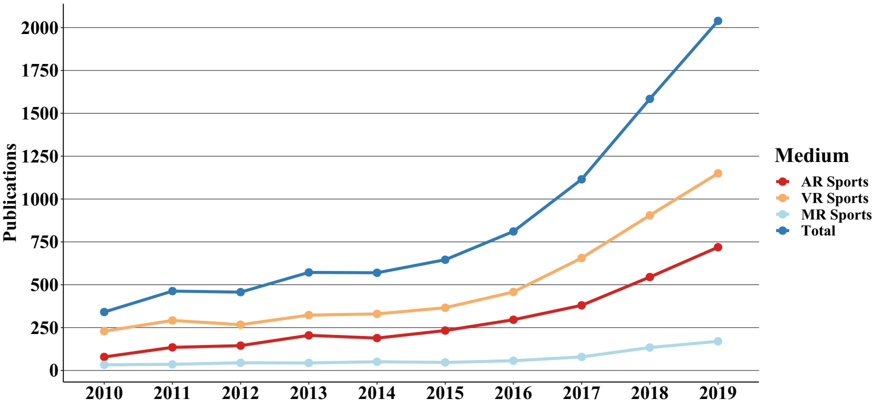

Fig. 14.2 Yearly publications in the area of sports for augmented, virtual, and mixed reality between 2010 and 2019

displays (HMDs), CAVE solutions, or standalone VR systems (e.g. Oculus Quest[4]) [16, 39]. Also, in the area of science and research, the interest in immersive media increases steadily. Figure 14.1 illustrates the aggregated number of publications per year searching four scientific databases (PubMed, Google Scholar, ACM Digital Library, and IEEE Xplore). This includes augmented reality (AR), virtual reality (VR), and mixed reality (MR). Comparable results could be found in the area of sports as depicted in Fig. 14.2. Reasons for an increasing interest are among

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[4] https://www.oculus.com/quest/.

others a high level of control and monitoring possibilities of various stimuli. Further, due to the immersiveness of these technologies, sophisticated metrics can be derived to research human behavior as it is already done in education and rehabilitation [17, 37, 59]. Additionally, development environments like Unity[5] and Unreal Engine[6] provide an easily accessible development of VEs, since they already contain integrated components that allow the simulation of a realistic physical behavior (e.g. gravity and other forces) of virtual objects.

These technological developments of XRs also evoke potential for behavioral assessment and training in extreme environments. One example is the emulation of conditions experienced by astronauts during training at National Aeronautics and Space Administration (NASA) facilities or the simulation of urban combat training practicing command and control skills, decision-making, and situation awareness [42, 64]. Comparable to combat training also elite sports benefits from such technology. In elite sports, where a holistic understanding of athletes is required, XRs can provide realistic simulations enabling a sophisticated evaluation of performance parameters (e.g. psychological, psychophysiological, or personality aspects) and decrease injury risks for athletes at the same time [6, 24, 78]. This not only eases the process of individualized training but also yields potential in talent scouting and development. Furthermore, XRs facilitate the use of assessment and training environments that would be costly to create in the real world (e.g. a simulation of a cheering crowd as a stressor) and provide an individual adaption of the environment in real-time [76]. Advances in indoor localization allow large-scale play areas to be experienced in XRs [20, 24].

In this work, we provide an overview of XRs and their potentials in extreme environments focusing on elite sports. Therefore, first, the necessary basics, like stereoscopic vision, essential for the understanding of XRs are explained. Further, quality measures of immersive environments are discussed by defining the individual aspects of the concepts of immersion and presence. Characteristics of XRs are described and design considerations will be presented for the development of immersive environments in elite sports based on results of previous research. Overall, the goal of this work is to develop a strategic vision for XRs and their applications in elite sports. The long-term potential will be evaluated including opportunities and barriers. Finally, derived from the resulting design considerations, we suggest a research and development agenda for the field.

14.2 Extended Reality Technology

As an umbrella term, XR covers different approaches that combine the real and virtual world. These are AR, MR, and VR. Whereas AR and MR create an overlay

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[5] https://unity.com/

[6] https://www.unrealengine.com/

in conjunction with the real world, VR completely immerses the user into a virtual world [50, 67]. Despite the great potential and growth, XRs still struggle to gain user acceptance [15]. One hurdle for a mass-market acceptance is the cost-intensive hardware needed to experience different forms of XRs. To define future research topics, we will further address limitations and challenges that need to be overcome to make such technologies accessible to a broad variety of users. In this section we explain the fundamental principle of stereoscopic vision for XR technologies and give an introduction to the reality–virtuality continuum, which emphasizes characteristics of the named immersive technologies. Further, we introduce concepts and guidelines for immersive user experience, which will function as a basis for the introduced design considerations in the addressed application area of elite sports. Additionally, we give a brief overview of XR history and deal with the different theoretical concepts developed and their adaption over time. To do so, we focus on optical sensory feedback only. Other influencing criteria like sound or haptics, which also play a role for immersive experiences, are not considered.

14.2.1 Stereoscopic Vision

To understand the concept of how depth perception is created for the user within immersive VEs, the fundamentals of humans' stereoscopic vision are outlined. The following explanation includes the neuronal system of the brain, which fuses the visual input of the right and left eye's retina to one single perceived image [56]. First, the physiology of each eye is explained and secondly, the interplay of both eyes is discussed in more detail.

When light passes through the lens of the eye, the direction of an object in space is perceived, besides the obvious perception of brightness, color, and shape. This perception of an object's direction in space is determined by the directional values (local signs of Lotze [43]) of the stimulated retinal areas. These directional values were found to be an intrinsic property of the eyes since inadequate stimuli (external mechanically applied pressure on the eyelid) showed the same directional localization of stimuli. Given that the direction of an object in space is perceived, the eyes are able to turn toward this object. This turning movement of the eyes, also called saccade, is highly precise. By doing so the object is imaged on the fovea, which is the region of highest visual acuity [56].

Up to this point, the described phenomena hold for each eye independently. However, to perceive depth the two eyes need to work together and create one single visual impression. The basis for this relies on the directional values or local signs of each eye. If an object is fixated using both eyes, each eye will hold independent directional values but still the image is not perceived as an overlay of both visual impressions at the intersection of both eyes' directional lines. Instead one single image is perceived that seems to originate from in-between both eyes. This phenomenon is often referred to as the central imaginary eye, or the cyclopean eye [32, 33], and reveals the connection between the eyes. The above-mentioned fixation behavior leads to the object imaged on the foveae of both eyes. The resulting fusion of the images shows that the areas of the foveae of both eyes correspond to each other. Only if images are projected onto corresponding areas, the images can be fused, otherwise double vision occurs. Thus, if an object is fixated and the object is successfully projected onto corresponding areas, they share common directional values. Unsuccessful projection can be caused by strabismus, which is a misalignment of the eyes. In recent articles, it is argued that VR can be used to measure the extent of the misalignment to compensate for the unsuccessful projection [47, 48]. Such a correspondence not only can be found for the foveae but also for every other area of the retina that shares common directional values [56]. The perception of a single visual impression that relies on the excitation of corresponding retinal areas is called sensory fusion [56].

With these fundamentals of sensory fusion in mind, consisting of monocular and binocular effects, the horopter is discussed. The horopter shown in Fig. 14.3 describes the distribution of the corresponding retinal areas given a fixation point. In Fig. 14.3 the fixation point is FP. The horopter is of circular or elliptic shape around both eyes and marks the position at which an object P disparate to FP is perceived as one fused visual impression of that object [56]. Vieth [75] and Müller [53] expected the horopter to describe a circle, which can be seen in Fig. 14.3 as the so-called Vieth–Müller Circle or short VMC. However, actual experiments by Hering [33] showed that the horopter describes a flat ellipse. This empirically determined ellipse is called the empirical horopter or short EH. Figure 14.3 illustrates the difference between the geometrically constructed VMC and the data-driven EH.

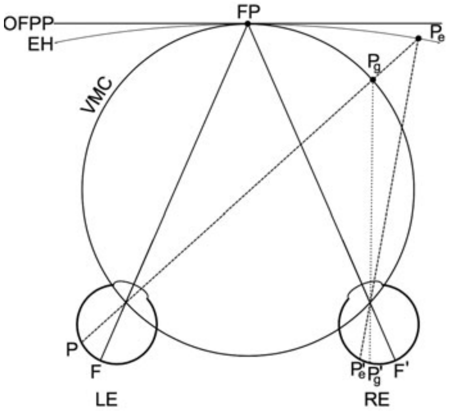

Fig. 14.3 Geometric and empirical horopter. OFPP marks the objective frontoparallel plane, EH the empirical horopter, and VMC the Vieth–Müller Circle or the geometrical horopter. FP is the fixation point for the central gaze. P_e and P_g indicate objects on the empirical and geometrical horopter. F and F' are the foveae of the left and right eye. The point P is the location on the left retina where P_e and P_g are imaged. The object on the empirical horopter at position P_e is seen as a fused image. The object on the geometrical horopter at position P_g is perceived twice as it does not fit the properties of corresponding areas. Figure according to [35]

Given that a point FP on the objective frontoparallel plane (OFPP) is binocularly fixated, this point would be imaged on the foveae F and F' as corresponding retinal areas of both eyes and thus this point is perceived as one single visual impression. In addition there is an object P that is also perceived as single visual impression while still fixating FP. This means that the object P must be imaged on the corresponding retinal areas of both eyes. For the left eye LE, this object is imaged on the retinal area P. According to VMC, the object must lie on the circle at P_g, and results in an excitation of the retinal area P_g' in the right eye RE. The true position of object P, however, is on the empirical horopter EH that excites the retinal area P_e'. In fact, if P lies on VMC, the observer would perceive the point twice.

Hence, stereoscopic vision combines monocular and binocular functions, processing the two slightly different perspectives captured due to the distance between the eyes. Most immersive technology-based simulations apply this principle for creating depth perception. Therefore two images are displayed, one for each eye, to create a realistic stereoscopic environment based on virtual scenes rendered from two different perspectives. Thus, in terms of designing new immersive devices, especially stereoscopic vision as a combination of monocular and binocular functions needs to be understood to create the basis for realistic VEs. Not only fully VEs would benefit from extended knowledge of stereoscopic vision but also the mixture of reality and virtuality since this enables virtual objects to seamlessly blend into the real environment and behave or appear more naturally. The different arising possibilities between reality and virtuality are discussed in the following sections.

14.2.2 Extended Reality Continuum

For human beings interacting with their environment, multiple collaborative sensor modalities are required. Smell, taste, touch, hearing, and sight are enablers allowing to create a holistic image of the (possibly virtual) environment and react to it accordingly. For spatial orientation and perception of stimuli, visual perception is the most pronounced sense, since it is accurate in all three dimensions of space [38]. The design and development of XRs strive to follow those requirements by providing digital layers that try to elicit realistic multi-modal sensory feedback. The principle of stereoscopic vision, therefore, functions as a driver for experiencing three-dimensional and context-based information. Regarding visual sensory feedback, the possibilities of immersive technologies can be described by the so called reality–virtuality continuum (RVC) [50]. Based on this continuum, different design patterns and implications, frameworks, and concepts are derived in various domains. Under the influence of technological development, these approaches are to be regarded as dynamic and hence can differ along with different application areas.

In their early work regarding mixed reality and the RVC, Milgram and Kishino distinguish six different classes that can be used to define a VE. Within their described taxonomy, key values are the interactions with real or virtual objects, real or virtual images, and direct or non-direct viewing of these artifacts [50]. This leads to three dimensions naming the extent of world knowledge, reproduction of fidelity, and presence metaphor. Whereas the latter describes the extent of illusion the user is in, reproduction fidelity determines the level of realism for an experienced VE. The third dimension specifies the degree of knowledge existing regarding the displayed world. Based on these fundamentals, the derived RVC includes real environments on the one end and fully immersive virtual environments at the opposite extremum. Related to elite sports, real-world scenarios are also called in situ scenarios as they let athletes perform tasks in an environment that consists purely of real objects. Contrary, VEs solely consist of virtual objects and immerse athletes into a purely digital world. This may include, but is not limited to, a certain level of interaction between the environment and the user. Milgram and Kishino describe the space in between these two extremes as MR. MR comprises real and virtual objects that are presented together within the user's FOV. This continuum is defined to distinguish among the technological requirements necessary for realizing and researching MR displays. Based on the taxonomy of Milgram and Kishino, we propose a slightly different concept for categorizing XRs [50]. The main concepts can be described as follows.

14.2.2.1 Reality

Even though XRs are not required to experience the real world, it is important to understand and consider decisive aspects that influence human behavior within this world. Reality can be seen as the state or quality of being real. Real objects are characterized by their existence independent from any conscious entity observing them. Additionally, every individual perceives a subjective reality. It is based on the interpretation of the real world by the human mind and is influenced by factors such as previous experience and individual belief in what is true [28, 38]. Within this work, the reality is seen as an environment that can be experienced without the need of any artificial enhancements like wearable displaying devices. Hence, it is the space where humans can interact naturally with artifacts. Knowledge regarding human behavior within this environment can be seen as a prerequisite for designing XRs [28, 38]. Ideally, virtual simulations would imitate and/or extend reality so accurately and in such detail that they are indistinguishable. Consequently, the user would be unable to differentiate these concepts.

14.2.2.2 Augmented Reality

There are many definitions for the term AR [3, 22, 65]. The core idea of AR is to provide an information layer consisting of digital objects and cues for the user as an addition to the real world. This superposition takes place in real-time with the possibility for the user to interact. Crucial for this technology is the user being mainly exposed to and immersed in reality. AR, therefore, represents an unobtrusive, real-time extension to reality, which registers real and virtual objects with each other. In AR digital content can also be utilized to occlude real-world objects and hence changing the perception of the user [65, 71].

14.2.2.3 Mixed Reality

MR enhances AR in the sense that it mixes the real and digital world such that they are perceived to exist together in a shared environment. Important key factors are that digital information is displayed in real-time considering context-based real-world information. Therefore, tracking systems are utilized to detect the user's environment and modify properties of digital objects like size, orientation, or visibility dependent on the real world. Real and digital objects show a coexistence and dependency among each other in an MR world and are not limited to having a digital layer partly connected to real-world information (e.g. Google glasses displaying ratings of a restaurant). Instead, MR environments anchor virtual objects to the real world. A further characteristic of MRs is that the real world is the dominant world and hence is the fundamental ground truth for creating MR environments. The user interface of an MR should facilitate the user to interact with real and digital objects the same way. At the same time the relationships and dependencies between objects should be retained unless deliberately changed by the user [60, 71, 82].

14.2.2.4 Virtual Reality

Contrary to reality, VR defines the opposite extreme of the extended reality continuum. VR immerses the user in a fully computer-generated environment, which can be experienced through artificially created sensory stimuli and interactions comparable to the real world. Therefore, the principle of stereoscopic vision is applied to create depth perception by displaying slightly different images to each eye of the user, creating binocular vision. In a VR environment, the user is mostly cut off from reality and hence the VR environment is to be seen as the dominant world [38].

One special form of VR is the so-called augmented virtuality (AV). AV includes real-world objects into a computer-generated world. Sensor systems are used to track and include real-world objects into the VE. Even though AV incorporates a digital image of a real-world object, the environment still consists of computer-generated content (e.g. video see-through devices) [38, 50].

Based on the introduced forms of extended realities and the RVC suggested by Milgram and Kishino, we propose in this work the extended reality continuum (XRC). As illustrated in Fig. 14.4, it yields the three main concepts of AR, MR, and VR. Whereas AR is characterized by consisting of two overlaid layers (real and digital) that do not necessarily have dependencies among each other, MR as an enhancement of AR provides anchoring of digital objects in the real world. Such a mixture also requires dependencies and relationships between those two types of

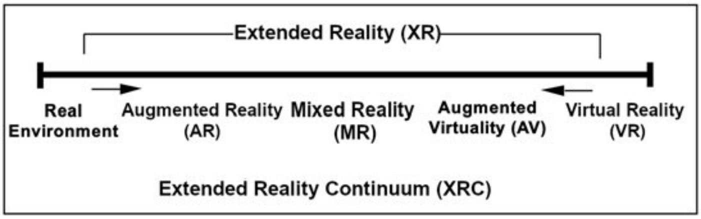

Fig. 14.4 Illustration of the extended reality continuum inspired by Milgram and Kishino [50]

objects (e.g. occlusion of objects from a specific perspective). VR and AV fully immerse the user into a computer-generated environment, which ideally enables an interaction comparable to a real environment. Even though this classification may provide a good overview of XRs, it is barely possible to define clear boundaries between the different concepts. Therefore, future research will need to create principles and devices that interweave these concepts. This requires responsive design thinking for future work (e.g. Microverse by Magic Leap), which facilitates to experience different forms of XRs dependent on the context of the user.

14.2.3 XR History

Already in the 50s the first immersive systems were developed incorporating stereoscopic vision. One example is the Sensorama VR machine developed in 1957. It is supposed to be one of the first VR devices including stereoscopic vision, haptic, and taste feedback [31]. In contrast to this arcade machine-like system, Ivan Sutherland designed the first HMD in 1968 called the Sword of Damocles. The name was derived from the fear of subjects being decapitated in case the HMD mount would detach from the ceiling. Nevertheless, the Sword of Damocles by Ivan Sutherland can be seen as the origin of modern wearable HMDs [73].

The Virtual Interface Environment Workstation (VIEW) developed in 1990 by NASA was the first VR system capable of full-motion tracking. Displaying and interacting with computer-generated content was enabled using a wide FOV HMD combined with fiber optic cables and sensor enhanced gloves and suit. The system was capable of tracking motions, bending, gestures, and spatial orientation of the wearer. Additionally, remote video cameras facilitated the incorporation of the real environment [21].

Between 2000 and 2012 the use and development of new VR systems was mostly limited to government, academic, and military laboratories with only little mass media attention. This period is known today as the VR Winter [38].

The advent of the third generation of VR headsets was initiated in 2012. Under the leadership of Palmer Luckey and John Carmack, Oculus[7] developed a controller

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[7] https://www.oculus.com/rift/.

supported and fully trackable high-performance HMD, which formed a new era of VR. While the first versions of these devices were still wired to a processing unit (PC), succeeding devices like the HTC Vive Pro[8] facilitated higher resolution and frame rates using wireless data transmission. Characterized by inside-out tracking, the next level of VR technologies like the HTC Vive Focus[9] or Oculus Quest[10] are not dependent on remote tracking and processing units. Therefore, they can perform as standalone devices with increased wearability and provide high-quality content at the same time [38, 67].

Beyond the Sword of Damocles, which was an augmentation of reality, but is nowadays broadly seen as VR technology, in 1975 Myron Krueger designed one of the first AR systems called the Videoplace. It combined video cameras and projectors to emit on-screen silhouettes to create an interactive augmented environment [41].

In 1992 Louis Rosenberg created Fixtures. It is defined as an overlay of augmented sensory information on a workspace to improve user performance. The device uses a full-body tracking exoskeleton and binocular display headset to facilitate interaction with digital objects projected in the real environment [61, 62].

With the commercial sale of Google Glass[11] in 2012, AR wearables came into the focus of the mass media. However, the launch of Google Glass was discontinued just two years after its release because of strong privacy concerns associated with the omnipresent video recording of the embedded camera. Nevertheless, Google Glass is considered a milestone for AR technology and the next generation (Google Glass Enterprise Edition 2[12]) is dedicated to helping companies develop AR solutions for employees [2, 67].

The development of the Microsoft HoloLens[13] and the Magic Leap[14], in 2016 and 2018, respectively, started the era of MR headsets. Defined as enablers for the context-based interaction paradigm, these devices use their integrated sensor system to scan the environment of the user. The interpretation of this information facilitates the melting of real and digital objects. Their high computational power makes it possible to interact with complex 3D models in real-time.

With the increased availability of computing capacity, future developments will strive toward devices that are capable of holistically covering the XRC and thus show high scalability for merging real and digital environments. As technology continues to improve, the possibility of designing valuable XR applications in various domains increases. This requires the development of different design processes and frameworks to create user-friendly interfaces. To evaluate the associated immersive

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[8] https://www.vive.com/us/product/vive-pro/.

[9] https://enterprise.vive.com/us/product/vive-focus/

[10] https://www.oculus.com/quest/

[11] https://www.google.com/glass/start/

[12] https://www.google.com/glass

[13] https://www.microsoft.com/en-us/hololens

[14] https://www.magicleap.com/

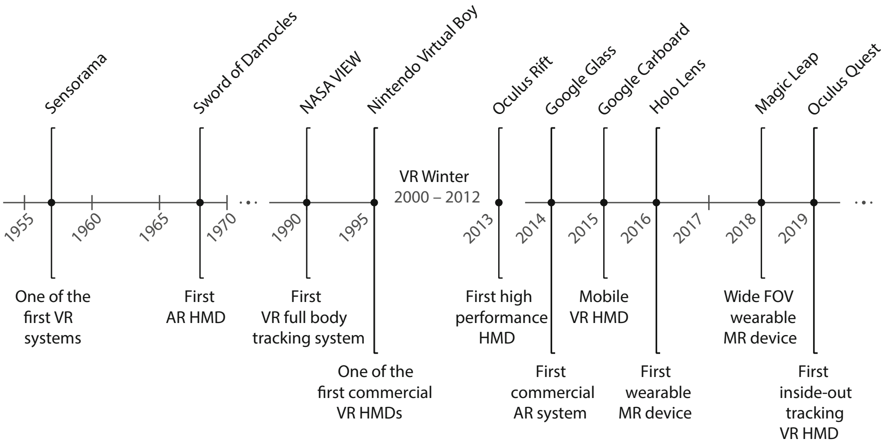

Fig. 14.5 Evolution of XR technology and its related most prominent developed hardware devices. XR pioneers like Morton Heilig (Sensorama) [31] and Ivan Sutherland (Sword of Damocles) [73] laid the foundation for modern standalone devices like the Oculus Quest and Microsoft HoloLens already in the 50s and 70s, respectively

environments, it is necessary to define and understand characteristics of and quality measures for XR environments (Fig. 14.5).

14.3 XR Quality Measures

For a model to be able to quantitatively categorize implementations and provide a quality measure for XRs, there is a need to establish a formula that can be used for such quantization.

The sense of presence is defined as the feeling of being there in a VE [70]. It describes how immersed the user feels and is therefore one of the most important characteristics for implementations. Even though presence is largely a subjective feeling of the user, in contrast to the objectiveness of immersion, there are still some parameters that were identified as having a direct influence on this feeling. Jason Jerald defines presence ρ as a function of user υ and immersion ι [38].

$$\rho = f(\upsilon, \iota) \tag{14.1}$$

This means that if the user closes his eyes, $\upsilon = 0$, experiencing presence is effectively not possible. On the other side, if ι is a function of the hardware components, in case the display malfunctions, this will also be zero and hence prevent the feeling of presence. Of course in both cases the factors within those functions, presented in the next sections, likely have additive components, so a complete loss of presence only happens when all hardware components fail, not just the visual system. They are mostly unknown yet and the only thing we know for sure are their zero conditions described above already.

It seems reasonable to define that if $\rho = 0$ there is no presence expected in a simulation. On the other side, $\rho = 1$ could indicate that the presence feeling inside the simulation is maximal and the feeling will not be distinguishable from reality.

To determine a formula for user and immersion, more complex measures need to be derived. We will present a concept to do this as part of an index, the higher the index, the larger the immersion or the presence capabilities of the user and thus, ultimately, the quantified presence index.

This model is derived from the definitions found in the works of Jonathan Steuer [72] and Jason Jerald [38], which in turn are directly influenced by Slater and Wilbur [69]. For example, for immersion, they define terms like vividness in the output of a VR hardware system and extensiveness, matching, and interactability in the input to this system. An additional term is the plot within the virtual world itself.

It needs to be stressed at this point that we have built this formula empirically from our and previous literature knowledge, it is not yet validated. It should be seen as a proposal that future work can build upon and parameterize it using appropriate studies.

The Model for the User (Presence)

Factors influencing the presence capabilities of the user are:

1. The physiological ability to make use of the vividness and interactivity of the XR hardware equipment and the mental capacity to comprehend the plot inside of the virtual world.
2. The prior experience regarding the use of an XR system, i.e. if users have no clue how to navigate the VE using handheld controllers, it is very likely that they will not feel the same kind of presence through interactivity.

For the physiological ability U of the user, we will distinguish six categories: visual U_v, auditory U_a, scent U_s, temperature U_t, haptic U_h, and other U_o physiology. For each of these categories, three states are possible: not impaired (3), partially impaired (2), and completely impaired (1). The latter means that the user is not able to receive any stimuli via this part of their physiology, e.g. because of physiological disabilities. The first five categories are related to physiologies that current hardware,[15] and probably that of the near future will be able to manipulate.

For the prior experience U_{xp}, we also define three possible states: no experience (1) with computer-based controllers or headsets, irregular experience (2), or routinely experienced (3) from almost everyday use of such systems. This comes naturally from the thought that we learn to manipulate our real world as infants with our hands, and presence can only be felt equally to reality if we can operate/manipulate a VE just as naturally as we would use our hands. It becomes clear here that this parameter needs to be a function also dependent on the input

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[15] See for example https://feelreal.com, in addition to current VR headset technology.

hardware that is used. If the hardware system is so advanced that it detects the human hands flawlessly and allows their use in the VE without errors, this parameter of the user becomes irrelevant.

With these definitions, our model for υ will be

$$\upsilon = f(U_v, U_a, U_s, U_t, U_h, U_o, U_{xp}). \tag{14.2}$$

For example, we imagine that a semi-parameterized model could look something like this (all parameters are randomly picked for demonstration):

$$\upsilon = \frac{U_v}{2} \cdot \left(\frac{U_a + U_s + U_t + U_h}{8} + \frac{U_{xp}}{3} \right) \cdot \frac{1}{3} \tag{14.3}$$

The Model for the System (Immersion)

Factors influencing the immersion capabilities are:

1. The degree to which the users' senses are covered with hardware input/output devices and their quality of mapping to the senses, defined as I_{sm}.
2. The responsiveness of the entities in the VE to user actions I_{vo}.
3. The plot of the simulation, how engaging it is, and how responsive/complex it reacts to user decisions I_{vr}.

The first item consists of the presence model for physiology. For visuals, two factors are important: the quality of the display I_q (e.g. pixel density) and the quality of the optics in general I_o (e.g. full coverage of the FOV with no noticeable distortion).

For the quality of the display, Apple introduced the term 'Retina Display' [34], describing a display where the user is not able to discern individual pixels anymore and sees the image as if it was from the real world. The corresponding pixel density equation can be used also for HMDs, and there are some headsets that already support this.[16] This term will be 1 if a full retina effect is achieved by the hardware.

The term for the FOV could be estimated with being the percentage to which the maximum human FOV is covered. If a 210 ° FOV is assumed for the human visual system, the formula would be

$$I_o = p * \frac{F}{210^\circ} \tag{14.4}$$

where F is the horizontal FOV of the headset used in the study in degrees and p is a parameter that can represent a possibly constant or nonlinear correlation of the model to its actual impact on immersion.

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[16] See https://www.techradar.com/news/new-vr-headset-offers-truly-retina-resolution-for-an-immense-price.

These two terms are only exemplary for the model of course, and we will not go into extensive details like also specifying the refresh rate of displays, which also plays an important role. Those elements need to be compiled in extensive evaluative studies or collected from existing ones. For now, we assume they contribute in a certain way to the sense-mapping model as

$$I_{sm} = f(I_o, I_q, ...) \tag{14.5}$$

With this, the general model for immersion can then be defined as

$$\iota = f(I_{sm}, I_{vo}, I_{vr}) \tag{14.6}$$

Now, both elements of the objective ρ-function are defined on an abstract level and show how such a concept can be narrowed down to more approachable levels.

14.4 Virtual Fidelity Characteristics of XR in Elite Sports

Virtual fidelity of XRs can be seen as the degree and effects of a system recreating a real-world experience or behavior [23]. Determining the virtual fidelity of a VE yields the possibility of systematically investigating its effectiveness regarding a certain task or goal. Different dimensions like display, interaction, or simulation fidelity can be considered when classifying the virtual fidelity of a system.

Previous research could show that striving for a high degree of realism when using XRs increases behavioral, emotional, and mental engagement and hence can have a positive impact on different tasks like learning or treatment of anxiety disorders [7, 11, 14]. In sports, this potential can be used to optimize assessment and training processes addressing cognitive and motor skills of athletes. Precisely, transferring and hence applying skills learned using a virtual simulation to a real-world task plays a key role from a sports science perspective [63]. Based on this assumption, it could be concluded that XR simulations should strive to replicate reality as closely as possible to enable an effective transfer of learned skills. However, from a sport science viewpoint, the requirements for XR visual fidelity are ambiguous. There is literature arguing that addressing and training isolated individual skills like pattern recognition on a non-task related basis (i.e. using an abstracted simulation) can be beneficial and hence neglects the need for detailed reproduction of realistic scenarios [5, 49]. Contrary, there is work suggesting to seek for a high level of context when creating VEs for sports applications (e.g. a soccer simulation that provides a high biomechanical symmetry of agents to train decision-making under pressure) to optimize the skill transfer from the virtual to the real world [19, 55]. Due to these different perspectives, the understanding and usage of a visual fidelity framework for creating XR sports simulations as a support for design decisions is even more relevant (Fig. 14.6).

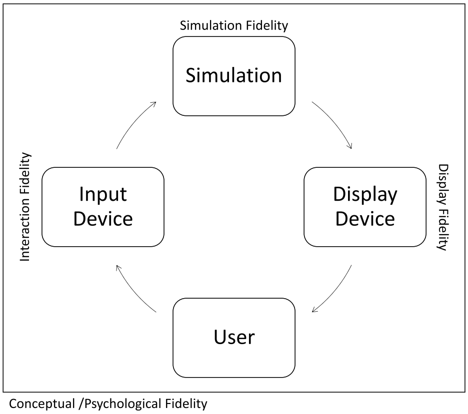

Fig. 14.6 The Simulation Information Loop from [8, 44] extended with the concept of psychological fidelity. For design purposes of XR applications in sports, it is necessary to frame the implementation into a conceptual plausible context that defines the level of cognitive demand and emotional attachment to clearly define training and assessment conditions

14.4.1 Types of Fidelity

Fidelity has different aspects, depending on the perspective. Whereas there are different approaches that address the physiological and psychological fidelity a user interface provides, it also considers system-dependent characteristics like display fidelity and input veracity.

14.4.1.1 Interaction

Physiological or also called interaction fidelity represents the degree to which a physical action is implemented within the virtual world comparable to real-world action. It can be divided into biomechanical symmetry, control symmetry, and input veracity.

Biomechanical symmetry defines the degree to which body movements are reproduced in the virtual world compared to the real-world movements in terms of kinematic, kinetic, and anthropometric characteristics. Whereas the latter describes the accuracy of body segments involved, kinematic symmetry addresses the degree to which a body motion is reproduced during an interaction compared to the real-world task. Further, kinetic symmetry defines the precision of forces involved in the interaction analog to the conducted task [8, 38, 46]. Imaging a VE in which goalkeepers have to anticipate the trajectory of the ball and determine the final destination by stepping into this position. The anthropometric symmetry would be high since legs and arms are used to change the position and catch the ball. There is no possibility to catch the ball, but indicate the final ball position by moving the whole body. Consequently, this scenario yields a low kinematic symmetry. The kinetic symmetry of the environment can be classified as low, since for the ball impact, there is no tactile or haptic feedback.

Control symmetry emphasizes the congruence between the control within a real-world task and its digital counterpart. Therefore, the degree of user actions that can be translated into effects within the simulation is defined as control. It is described by the three sub-components: dimensional, transfer function, and termination symmetry. How the input is interpreted and compiled into output effects defines the transfer function fidelity of a system. High fidelity, in this case, means that the interaction of the user has a comparable impact on the digital than on the real world. The dimensional symmetry determines the similarity of the usable interaction dimensions for a task in the real and virtual world. The stop of the interaction is defined by the termination symmetry [45, 54]. An example of a high control symmetry would be live tracking of an athlete using a motion capture system while performing a penalty shot. Since the legs are tracked and enable 6-DoF, the athlete is able to manipulate the ball within the virtual world the same way as in the real world. Hence, a precise transfer function is given and high-dimensional fidelity is achieved. The interaction ends the same way as it would be in the real world namely by kicking the ball.

The degree to which a specific input system detects and measures actions of a user is called input veracity. Characteristics of input veracity are the accuracy, precision, and latency. Thereby accuracy describes sophistication of the input system model to read and describe the individual interaction steps of the user. The precision symmetry defines the degree of exactness a system is capable to reproduce results under the same conditions. The duration difference between the user input and the sensory feedback of the system is defined as latency. The input veracity is mainly dependent on hardware components, like the input tracking system and the data processing unit. For example, an optical motion capture system (e.g. Qualisys[17]) with a tracking error of a few centimeters yields high input veracity. Contrary, position tracking limited to acceleration data can show low input veracity, since the needed operation of double integration can cause an inaccuracy that leads to much higher error rates in position tracking [38, 46].

14.4.1.2 Psychological

Whereas the previous described physiological aspects play a key role in almost every context of XR, especially in the area of sports assessment and training psychological fidelity is of equivalent importance. Psychological fidelity emphasizes the exactness to which an XR represents the underlying psychological processes of the corresponding real-world task and consequently leads to an identical stimulation of an

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[17] https://www.qualisys.com/.

athlete. In this context, a high or absolute fidelity is achieved in case the XR and its individual objects behave equally to the real world. This can for example be different in the speed and generated forces experienced during walking [80]. When having a low or relative psychological fidelity, absolute values like speed or forces of motion might be different from that of the real-world scenario but change in the same way within the XR. It is important to know that physiological and psychological fidelity are not competing concepts, but complementary [26, 40, 51, 52].

14.4.1.3 Display

Display fidelity is the objective fidelity of a display system and describes the accuracy with which a system can reproduce sensory stimuli. As stated by Bowman et al., display fidelity is a continuum that can level from low to high, rather than being a binary value. In this case, reaching the highest fidelity would mean that the virtual created content is not distinguishable from real-world content [9, 10, 50].

The concept of display fidelity encompasses a broad variety of objectively measurable factors. Previous research has identified the following visual aspects to influence display fidelity [38, 69]:

- Stereoscopy—displaying two images, each for one eye to simulate depth perception
- Field of view (FOV)—observable area users can see while using a display
- Field of regard (FOR)—area that can be seen when physically rotating the body or head
- Display size—dimensions of the display screen
- Display resolution—number of pixels displayed on the screen
- Frame rate—data frequency for re-rendering that is provided to the display
- Refresh rate—frequency of drawing rendered data on the display

An example for a display fidelity characteristic can be shown by FOV and FOR. A high FOV would enable a viewing angle of horizontal 135° and 180° vertical (natural eyesight) [32]. A high FOR would be achieved when providing a VE explorable by 360° in horizontal and vertical directions [38].

To determine whether a specific immersive type is more suitable for a specific task, Bowman et. al state that it is important to investigate individual factors of display fidelity. This can be problematic since it is difficult to isolate other influencing factors. Although the results obtained in a specific experiment might be generalizable, the state of the controlled factors could also have a significant influence on the results. It is also unclear for which tasks the users profit most applying a specific setting of display fidelity factors [8, 9].

14.4.1.4 Simulation

Another part of the fidelity spectrum is simulation fidelity. It determines the degree of plausibility and exactness with which real-world physics and characteristics are designed and implemented in an XR. This includes the description of attributes and behavior of objects within a virtual world and the VE itself. In other words how "real" the designed system can replicate the targeted environment [1].

In detail simulation fidelity incorporates physical and functional characteristics for an XR. On a physical level, the behavior of objects within the environment should be considered. This includes among others visual, spatial, and kinematic aspects. In elite sports, for example, creating a reaction task for training purposes should also consider contextual dependencies. The performance of a professional athlete might be different in an abstract (low) compared to a rich simulation including high visual representation and stimuli density. Likewise, this also impacts the efficiency for transfer learning. Functional characteristics describe the information and stimuli response of a VE. For example, during a decision task, this defines to which degree the VE lets users experience the consequences of their action. These characteristics are decisive since they influence the efficiency of training depending on the simulated task. Although simulation fidelity strongly interweaves with interaction fidelity, simulation fidelity focuses on the design and behavior of the VE and is therefore not necessarily user-dependent [30].

14.4.2 *Levels of Fidelity*

The concept of fidelity supports designers of interactive systems to make design decisions and evaluate theoretical frameworks. Fidelity is particularly important in cases of evaluation and training. Miller's pyramid shown in Fig. 14.7 illustrates the different stages of assessment in terms of learning. Whereas the evaluation of knowledge and compenetcies mainly investigates cognitive processes, performance and action focus on the actual doing of the learner and hence also include physical actions [51]. This definition helps to understand the required fidelity level of a

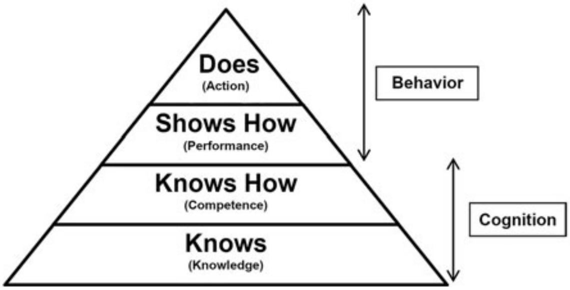

Fig. 14.7 Miller's pyramid of assessment adapted from [51]

system in terms of a specific task. Along with this framework, four different levels of fidelity can be distinguished for VE: (1) low fidelity XRs will be experienced least real for the user. This could be XRs with no to low interaction possibilities for the user with simple graphical object representations; (2) mid fidelity XRs are more realistic and allow more opportunities for learning. An example would be a goalkeeper training where the athlete is experiencing a penalty situation from a first-person perspective and is asked to predict the trajectory of a ball; (3) high fidelity is classified as a realistic simulation and enables a high degree interaction for learners in an environment that closely resembles reality. This is for example the above-mentioned goalkeeper scenario enhanced by a full-body avatar representation of the athlete and an enhanced kinematic and kinetic simulation of the penalty-taker agent. In such a simulation it would be possible for the athlete as goalkeeper to anticipate the direction of the ball by observing the body behavior of the agent. All body parts could be used for action; (4) true fidelity references to the real-world scenario. This applies in case a user cannot distinguish between virtual and real-world objects or scenarios anymore [44, 51].

14.5 Design Considerations

With the ongoing process of hardware development to blend the virtual and real world, the influence of XR technology in our daily life will increase steadily. This may one day lead to a true fidelity level, where real and virtual objects are perceived as equal. To amplify such a development, it is necessary to develop design guidelines and patterns, like it was done for the 2D-display paradigm [12, 68].

In the domain of sports the assumption for the optimal properties of the perfect athlete changed over the last decade. Whereas in former times the assumption of the average athlete (weight, size, etc.) seemed to be most promising among all sports, modern training approaches suggest to establish a high degree of individualization. This, on the one hand, applies to the athlete itself, but also to the form of sports. Nevertheless, within a specific sports assessing and training using a realistic and context-rich environment becomes more relevant. Isolated training of individual skills (e.g. cognitive flexibility) using abstract implementations of specific task theorems (e.g. assessing visual perception using 2D stimuli) may be applicable for specific purposes but is not seen as most valuable.

This new assessment and training strategy also demands new requirements for the development and research within this area. The following design considerations are created as a guideline to ease and structure the development and research of XR simulations in sports.

14.5.1 Standardized Quality Measures

Standardized quality measures should be established for being able to objectively assess the created XR. Measuring immersion and presence can be a decisive factor that influences an athlete's engagement and commitment [19, 55]. Further, it supports concluding the efficiency of a system and establishing a standard by facilitating benchmark measurements of the individual system [36]. This includes the level of reality and experienced presence of the user measurable using validated questionnaires designed for example by Banos et al. [4] or Witmer and Singer [81]. The immersion should be defined by placing the developed system along the XRC and describe hardware-based system properties (e.g. resolution or frame rate). To ease the way of placing a system along the spectrum, we suggest determining the ratio between real- and digital-world shares within the user's FOV (Reality–Virtuality Index).

$$I_{RV} = \frac{A_d - A_r}{A_d + A_r} \tag{14.7}$$

where:

- I_{RV} = Reality–Virtuality Index
- A_d = the proportional area of digital artifacts
- A_r = the proportional area of real artifacts

The application of the I_{RV} is not seen as an absolute quality factor for different XR applications but enables a precise classification of applications along the XRC. When considering a VR with solely graphical elements, the result of I_{RV} would be 1. Contrary, a completely real environment would achieve a score of -1.

14.5.2 Context and Task Plausibility

Another more sports science-driven requirement is a clear consideration and statement regarding the task and context plausibility. Therefore, the underlying cognitive demand and purpose need to be clarified. Psychological theorems should be described and the implementation of these constructs needs to be clearly stated. To ensure high quality in plausibility, expert ratings and assessments have to be applied to emphasize the validity of the task and context design (e.g. required simulation fidelity).

14.5.3 Familiarization and Experience Level

The level of experience is important in two ways. The experience in terms of technology and the level of sports expertise are decisive factors in this case. Previous studies could show that experts tend to feel less present in high-fidelity sports simulations and hence rate the simulation and attractiveness lower than their counterparts [77, 79].

Further, XR user interface should be developed responsive to the level of experience. Low and high experienced users should have the possibility to interact efficiently with the developed application by providing different options like shortcuts or additional attention guiding visual cues [18, 68].

14.5.4 Hardware Considerations

The variety of available consumer-grade XR hardware is wide and new headsets are consistently brought to market. Besides the continually increasing resolution, the number of stand-alone devices seems to rise, too. Such devices can be operated independently from any external computer, and most of these devices make use of inside-out tracking without the need of external tracking units.

If there is no connection to a high-performance computer required and no additional base stations have to be set up, the headset can easily be used at different places making the system more portable. Furthermore, the overall costs for such a system are decreased drastically since the computer is often the most expensive component.

Apart from all these advantages, there are also disadvantages. Stand-alone devices do not have the computational power required for high-resolution dynamic training simulations. As stated in Sect. 14.3, immersion and presence are important quality measures that influence user behavior and success. If the lack of computational power leads to low-resolution VEs and less responsiveness, immersion and presence are also decreased. This indicates a trade-off between portability and the quality measures.

Before starting the actual design, the place of action and the required immersion and presence should be considered revealing the suitable hardware for each application.

By the time this chapter was written, the Corona pandemic prompted governments to shut down public life. Even after shut down, the hygiene requirements were very strict leading to discontinuations of already running or postponements of planned studies. Not only the required distance between people but also the disinfection of hardware questioned the feasibility of such studies. Therefore, the possibility of hardware disinfection should also be considered when hardware is shared with a group of people especially performing sports tasks as well as the ease of putting on the headset to minimize contact between participant and supervisor.

Following these considerations indicates that the newest hardware is not always suitable. Desired immersion and presence as well as intended portability of the system are limiting factors that need to be pondered.

14.6 Conclusion and Outlook

This chapter aimed to define XR more precisely as a technology continuum and to show the current and future potential in sports. Therefore, different immersive technologies like AR and VR were classified and explained. Furthermore, quality features and characteristics of XR environments were shown and defined, which are important for the sports sector due to their general validity. Based on this analysis, design considerations for the use of immersive XR environments were derived.

The increasing interest and the use of XR in various disciplines such as science, entertainment, and gaming indicate a growing market maturity of this technology, which will continue to increase in the future. This has been demonstrated by the increase in scientific publications as well as the rising sales figures in the consumer market over the last few years. While VR continues to be the key driver in this technology sector, the use and thus the sales of AR and MR devices will also increase as technology develops. The next step in this development will be reached when devices are able to operate the complete XRC presented in this work and consequently can no longer be clearly identified as individual AR, VR, or MR devices. This new generation of XR technology will be able to prepare context-based content specifically for the user and thus generate a high level of immersion.

In order to better understand XR environments in the future and to be able to use them in a more targeted manner, further quality features and guidelines must be defined. In this work, we show a first approach to objectively formalize the important quality characteristics of immersion and presence. Future work should take up this approach to validate and optimize it through practical applications. This will also facilitate an accurate characterization with respect to the fidelity of different XR environments.

Especially, in the field of sports XR applications will mainly be used in elite sports, since currently expensive and maintenance-intensive systems like the SoccerBot[18] or high-end tracking systems (e.g. Vicon Optical Tracking[19]) are required. With the increasing availability of new XR systems such as the Oculus Quest, they will also establish themselves more and more in the low-cost hobby sector. These realistic simulations are particularly interesting, as they promise a very high learning effect and will therefore lead to optimization for many sports. Therefore, a standardization for such environments is necessary. More research is needed to understand the effects of different characteristics of XR environments. This requires

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[18] https://www.soccerbot360.de/

[19] https://www.vicon.com/

that both, researchers and developers are aware of the quality characteristics of individual XR environments and can continue to evaluate them in a standardized way. It is safe to say that XR technology will have a major impact on all areas of sports in the future and will also provide a fertile basis for the expansion and creation of new sports.

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