Beyond astronaut's capabilities: a critical review

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Abstract

Prolonged human presence in space has been studied extensively only in Earth orbiting space stations. Manned missions beyond Earth's orbit, require addressing further challenges: e.g. distances exclude effective tele-operation; travel times, distances and the absence of safe abort and return options add physiological stress; travel times require novel closed-cycle life support systems; robotic extravehicular activities require the development of hardware for semiautonomous exploratory, inspection and maintenance tasks, partly tele-controlled by human operators inside the spacecraft. These few examples suggest that if the endeavour of interplanetary manned space flight has to become a realistic future possibility, the technological support to astronauts will need to be substantially developed.

This paper critically reviews the current scientific maturity of a number of diverse and sometime controversial visions of possible solutions, and at the same time attempts to provide an overview on some new key technologies potentially able to enhance astronauts capabilities. The status of research on induced hypometabolic states is introduced together with the evaluation of its potential impact to space travel. Motor anticipatory interfaces are discussed as novel means to enable teleoperation, cancelling command-signal delays. Research results on brain machine interfaces are then presented and their applicability for space is discussed. Finally, liquid ventilation is assessed as a technology possibly suitable to extend the astronauts capabilities to withstand acceleration loads of significant magnitude.

The paper attempts to address the critical parts of each one of these concepts showing that, while sometimes considered science fiction, in some cases a number of scientific results already allow to be more optimistic and in other cases to locate at least the showstoppers that will need to be removed in order to successfully develop the corresponding technology.

Introduction

Recently, space agencies renewed their interest in exploration programs. In the white paper "The Global Exploration Strategy: The Framework for Coordination", drafted and endorsed by ASI (Italy), BNSC (United Kingdom), CNES (France), CNSA (China), CSA (Canada), CSIRO (Australia), DLR (Germany), ESA (European Space Agency), ISRO (India), JAXA (Japan), KARI (Republic of Korea), NASA (United States of America), NSAU (Ukraine), Roscosmos (Russia).[1], it is mentioned that *Space exploration is essential to humanity's future. It can help answer fundamental questions such as: Where did we come from? What is our place in the universe? What is our destiny? It can bring nations together in a common cause, reveal new knowledge, inspire young people and stimulate technical and commercial innovation on Earth.*

Following this vision, the present paper tries to assess the technological levels of some of our engineering solutions for the design of manned missions of prolonged duration. Allowing astronauts to "live in a tin can" is only one of the issues that engineers are confronted with. The limited capabilities in terms of mobility and coordination during any Extra Vehicular Activity (EVA), microgravity related loss of physical performance, the long communication isolation times, the signal delays during tele-operations add up, making manned exploration missions very demanding.

Some of these issues are expected to be alleviated by current technical development, and the manned exploration of the Moon or Mars appear today within the capabilities of an ambitious exploration programme. On the other hand, completely new technological solutions will be needed for the pursuance of human exploration of the solar system and beyond.

With this in mind, the Advanced Concepts Team of the European Space Agency [2] started in 2003 to address the areas of bio-engineering and biomimetics to find potentially revolutionary technologies and concepts and to assess their development status and their potential benefits for the space sector. This paper discusses a few of sometimes considered controversial concepts, with the objective of establishing their scientific grounds, of critically assessing their development status and of understanding their potential impact on future exploration programmes.

First, the possibility of inducing a hypomethabolic state on humans as a mean of reducing psycho-physiological stress in long duration travels is addressed, followed by the use of non-invasive brain machine interfaces and motion anticipatory interfaces as means to augment human capabilities to tele-operate increasingly sophisticated devices and finally to conclude by discussing the use of liquid ventilation for water immersed astronauts as a mean to improve the astronaut response to continous and impulsive high acceleration loads.

Induced hypomethabolic states

Motivation

When leaving Earth, humans have to cope with stress related to environmental conditions never before experienced during their phylogeny [3]. Even with spacecraft offering the state of the art of environment control, both psychological and physiological issues arise. The most prominent of them regard social isolation, physical confinement, reduced afferent flow in the central nervous system (CNS), hypokinesia, loss of circadian rhythms, symptoms due to increased radiation level, and loss of cardiopulmonary performance due to micro-gravity [4]. Furthermore, once in the space environment, it is rather difficult to discriminate the single effects related with their specific stresses.

Therefore the study of the effects and their potential solutions is mainly addressed in Earth-based experiments. An example for such a terrestrial study on the effects of the space-environment on human physiology is the EXEMSI study [5]. It has demonstrated that prolonged isolation effects body weight, blood volume, the regulaton of hormones rennin and aldosterone [6], and also the immune system [7]. On the other hand, a recent study on crew members of ISS and MIR reported extremely low levels of negative dysphoric, i.e. negative, emotions [8]. Having the "happiest employees" most likely results from the almost daily psychological support, euphoric attention from co-workers and the public as well as regular communication with their families and friends. As a result, space travelling has even been reported to have positive emotional and salutary effects on most of its participants [9, 10].

Obviously, the situation is rather different during an interplanetary (and even more so hypothetical interstellar) travel as close to real-time communication with ground control is impossible. During these missions, the effects of isolation are likely to be close to what was found in the EXEMSI study, unless they are counteracted by measures within the spacecraft. This will require far more and extended facilities concerning psychological and physiological health onboard than hitherto established including a way of automated psychological support to the individual [11, 12] with considerable consequences on spacecraft design (e.g. 75m^3 of pressurised living space per astronaut for a manned Mars mission as assumed by a recent internal ESA study [13]). A two years manned mission to Mars with six crew members would lead to a mass penalty associated with providing life support and a suitable environment of approximately 40% of the total wet mass. Only for food stowage, the Equivalent System Mass (ESM) - a measure taking into account both the quantity of consumable and the equipment required to maintain/deliver/manage it - is expected to be around 30 tonnes, not taking into account the mass associated with water and atmosphere provision and waste management. It therefore seems evident that innovative solutions for the life support system (LSS) cost will be critical for the feasibility of missions involving long travels [14].

An approach to drastically reduce human activity

During the time-consuming transfer to the final goal of an interplanetary mission, only minimal if any human activity and control will be required. As a consequence it would be desirable to reduce consumption of on-board resources during that time and somehow put the crew members "at sleep". Such behaviour can be observed in many hot blooded animals including mammals, i.e. animals related to humans, which hibernate in order to minimize energy consumption during times of reduced activity and food availability, i.e. winter [15]. While poikilothermic (cold blooded) animals such as fish or insects constantly adjust their body temperature to the ambient temperature, homoeothermic (warm blooded) ones such as mammals have to actively enter a state of reduced metabolism. This ability can be observed in different species belonging to different families. Within the class of the mammalians, these range in size from the ground squirrel (Spermophilus tridecemlineatus) to the brown bear (Ursus arctos) [16].

If put into a hypomethabolic state, humans would require less energy and food, they would produce less "waste", use less space, possibly face less emotional stress by not being consciously faced with its isolation, and finally could encounter a far reduced degradation in physical performance as it is usually observed during long times of inactivity [4]. Furthermore, the reduced ventilation, heart rate, kidney filtration and CNS activity could make the organism less sensitive to the deleterious effects of microgravity; the radiation effects are expected to be left unchanged instead.

If the positive effects of using hypomethabolic states appear obvious, there are still several difficulties to be understood better and mastered. One of the big open challenges is to artificially induce hypomethabolic states in beings that don't naturally enter into them.

First steps towards that goal have already been achieved: so far it is possible to induce hibernation in animals that are known as non-hibernators but that belong to the same family as hibernators. The synthetic compound DADLE (Ala-(D)Leu-Enkephalin), once injected, induces hibernation by mimicking the action of the Hibernation Induction Trigger (HIT), the natural hibernation trigger molecule in hibernators like ground squirrels, bats, and black bears [17]. The DADLE molecule is a modified form of enkephalin, a natural opiate usually found in the brains of mammals. Opiates cause effects similar to those observed during the mammalian hibernation, like bradicardia, hypotension, respiratory suppression, and lowering of set-point in thermoregulation. But there are still no proofs of hibernation on animals whose family never goes in hibernation state. However, the uniformity of DADLE as a trigger substance for several different taxa indicates that hibernation did not evolve parallel but has a uniform ancestor despite the individual differences. This suggests that the genetic program for allowing initiating hibernation might indeed be present in all mammals and only deactivated by a block of genetic transcription. Advances in genetic therapy and a more profound knowledge of the genome relevant for hibernation could enable to genetically turn on the hibernation-program which then is triggered by treatment or even ambient conditions. Support for this theory lies in the fact that at least some of the genes associated with hibernation, such as those involved with fat metabolism (PL and PDK-4) are already known to be present in the human genome [18].

The human-hibernaculum

Obviously, during hibernation an automated control of physiological parameters and the possibility to actively de-hibernate an astronaut would be necessary. This would be realized with what Ayre et al. described as a human-hibernaculum [4]. Ayre et al. argue that as the hibernation technique is still unknown, it is impossible to determine the exact requirements placed on the human-hibernaculum, but it is possible to have an idea on how such a device would look like assuming its main function would be to monitor and maintain a given corporeal condition.

Ayre et al. then proceed evaluating the hypothetical scheme of a space human hibernator and its impact on the global life support, which is reported schematically in Figure 1. As hibernating beings do not eat, drink, urinate or defecate, the components of a typical life support system are downscaled and partially omitted (see grey areas in Figure 1, taken from [4]).

For example, the atmosphere revitalisation component is still required to support the astronauts respiration, which continues in astronauts in an hypometabolic state but with a breathing and a metabolic rate that are drastically lowered if compared with normal sleeping humans. This also lowers the moisture transfer to the atmosphere through respiration/perspiration, with associated smaller quantities of waste generated from the atmospheric and water management functions. Then, water management and waste processing components would be positively downscaled too. The principal qualitative benefits in terms of payload mass and complexity for long term missions appear obvious but have still to be quantified.

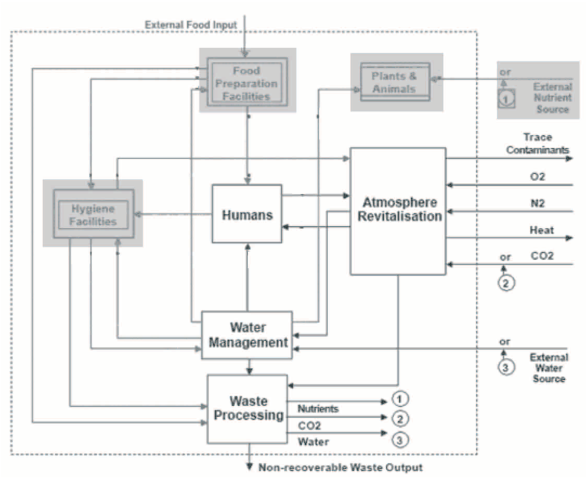

Figure 1: Human hibernation impact on a life support system as taken from Ayre et al. [4]

Neuro-Inspired Interfaces

Motivation

The high versatility of the human motor coordination allows for a huge range of elaborated behaviours, not even related with "evolutionary" taks, such as dancing, playing soccer, doing acrobatics or playing music instruments. On the other hand, one of the big limitations of human motor performance is that it is strictly bound to the physical conditions that govern our planet. Our perception and planning of movement, as well as the perception of the external movement in our environment, for example, is strictly related to the identification of the gravity axe. Inevitably, our sensory-motor system will encounter a loss of performance in situations of changed or annihilated gravity [3]. This loss is so important that, from certain perspectives, we can assume that astronauts are in a similar situation to people affected by motor disabilities [19]: both of them have, for opposite reasons, a deficit in the performances required to accomplish their motor tasks. On Earth, disabled people can take advantage of assistive systems, which are technologies designed to fill the gap between user's residual abilities and required ones [20, 21]. So, the answer to the reduction of physical and mental ability suffered by astronauts can be addressed (and it already partially is) with assistive technologies, once they are redesigned for functioning in space.

Interfacing Naturally

The required assistive technologies for astronauts are, essentially, robotic hands, arms, rovers, and so forth. Most of them are already technologically well developed, but are still lacking in operability. In fact, the reduction in motor coordination related with weightlessness conditions affects also the use of any kind of physical interface [22]. Moreover, even when complex robots are operated by experienced users on Earth, the open-loop control in real-time has been proved several times to be inefficient with the traditional physical interfaces [23].

The reason is that the interfaces are operated by predefined user's motor actions, and typically different action kinematics and geometries are associated with different interfaces (i.e. computer keyboards and mouse). The use of these interfaces requires a re-modulation of connections between the user's brain motor areas involved with the device utilization (i.e. the neuronal networks involved with the actual formulation of a sentence), and those dedicated to the motor task for the interface operation (i.e. the hand and fingers control to obtain a correct typing of this sentence). Obviously, operating a complex interface involves a high cognitive load which - when several different interfaces have to be operated within a short period - can easily decrease the operator's mental performance.

In consequence, there is a tendency to suggest the adoption of natural interfaces aiming to make the communication and control of the device easier for the user, and allow him to fully focus on the task instead of on the interface use [24]. A natural interface, with respect to the traditional ones, exploits user's natural communicative channels and hence allows intuitive and universal use without elongated training sessions [25]. The commonly studied natural interfaces integrate speech recognition, gesture recognition, facial expression recognition, and gaze tracking. Even though these interfaces have the potential to allow the control of complex systems, their usefulness for severely disabled people and - in an analogue way - for astronauts is arguable. The gesture and facial expression recognition cannot be efficient if the impaired user is not able to perform them precisely and speech recognition faces problems due to background noise (64 dBA for the air conditioning to 100 dBA for some vent relief valves in case of space stations)[3, 26, 27]. Gaze tracking alone is not enough precise and rich in contents to permit the control of complex systems.

Interfacing the brain

A new approach for control interfaces is based on the prediction of user's motor intentions. These intentions are not at all related with the user's abilities but can be read and translated in machine actions via a feedback loop. There are two basic approaches to "read" a user's motor intention.

One is the monitoring of involuntary movements constantly proceeding in time the intentional final movements [28, 29, 30] using a so called motor anticipatory interface (MAI). Another and more known technique is the identification of the user intention as it naturally origins in the brain, by using brain-machine interfaces (BMI) [31, 32, 33].

Brain Machine Interfaces

With brain-machine interfaces it is theoretically possible to restore or augment human communication and control skills [31], by directly interfacing the brain activity with the controlled devices. With a traditional interface, the messages and commands that a subject wants to express are organized in his dedicated brain structures and sent to the external world through the physiological pathways of corticospinal fibres and muscular fibres of peripheral nerves that connect the central nervous system (CNS) with the subject's muscles. The activity of muscles produces the movement required to operate the interface in order to obtain the physical expression of the intended message or command (see Figure 2 taken from [34]).

A BMI records the neural activity related with the message/command intention at the cortical level by an invasive or non-invasive brain activity's measurement system. This activity is decoded into the intended message/command, and finally actuates the user's intention by means of an external actuator (like a cursor on a PC monitor, a robotic hand, or a wheelchair) (Figure 2). Invasive systems directly record the electrical activity of a group of few neurons (usually about one hundred) via electrodes inserted in the user's brain cortex [35]. As demonstrated by Nicolelis [36, 37], by recording the activity of even such a small number of neurons randomly selected in the motor cortex, it is possible to decrypt the user's intended movement in a 3d space, and then to make a robotic arm replicating it in the real world. The monkeys used for these experiments succeeded in operating the robot without moving their own arms, as if the robot arms had become extra limbs of their own bodies. The invasive techniques require severe and currently still potentially dangerous neurosurgery operations, which are unsuitable on subjects not affected by severe paralysis. But paralyzed subjects don't have any natural feedback anymore, which makes the first training phase of implementation of these interfaces impossible, and their subsequent use largely ineffective [38].

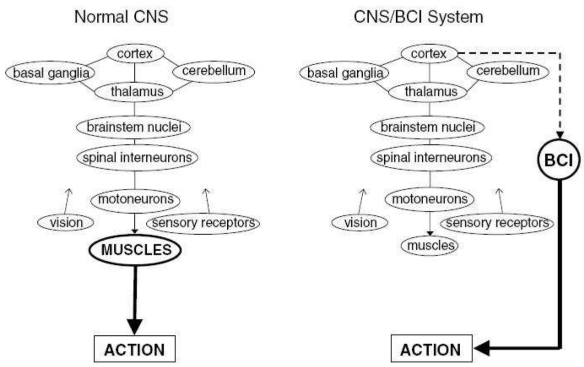

Figure 2: Different pathways from intention to action between tradicional and brain machine interfaces as taken from [34].

As a consequence, non invasive systems, which operate by recording the brain activity from "the outside" of the skull, appear today as the more suitable platform for studies on healthy subjects and, therefore, on astronauts [?]. The basic recording of brain activities takes place via well known clinical non invasive diagnostic devices such as electro-encephalogram (EEG), magneto-encephalogram (MEG), functional magnetic resonance (fMRI), positron emission tomography (PET), and near red spectroscopy (NIRS). Most of these devices have a poor temporal resolution of the signals (e.g. fMRI, PET, the current NIRS) and hence do not suffice for real-time operations. Both EEG and MEG however, do measure brain activity with the desired temporal resolution.

The EEG records the projection of the electric field generated by the activity of a large group of neurons on the scalp of the subject by surface electrodes. The MEG monitors, instead, the magnetic field associated with the same activity. The differences between them are apparent. The electric field produced by neural activity is shielded by the layers of protecting tissues and fluids that separate the brain from the outside world before being recorded by EEG instruments and in consequence, the spatial resolution is drastically limited, making the precise identification of the group of neurons generating the signal impossible. For this reasons, BMIs based on EEG did not even come close to achieve the capabilities of Nicolelis invasive BMI [33].

MEG-BMI Space Module

The same layers of living tissues and fluids are however "transparent" to the magnetic field. Accordingly, MEG instruments can identify with high spatial definition the topological origin of the detected activity. However, the magnetic field is so weak that, in order to detect it, the device has first to be wholly insulated from any other magnetic source (even Earth) by enclosing it in a room delimited by thick lead walls; secondly the signal can be successfully amplified only by mean via an extremely sensitive device such as cooled superconducting quantum interference devices (SQUIDs).

For the current general aim of studying BMIs as assistive technology platforms for disabled people, MEG-BMIs are too expensive, large, heavy, and not enough portable for most cases. Some of these constraints might be less unfavourable in a space perspective. The insulation chamber could be less thick and massive; future high temperatures superconductors might require less, or even no cooling at all, reducing the overall dimensions of the device. The portability is probably less problematic by implementing e.g. a MEG-BMI dedicated room.

Motor Anticipatory Interfaces

A rather unknown but potentially interesting approach to natural interfaces is the anticipatory one. The study of anticipatory interfaces originated in work on multimodal interfaces and natural interfaces. Generally anticipatory interfaces are defined as all those control apparatus able to identify user's intention not by explicitly given commands, but by monitoring involuntary user's behaviours and/or environmental parameters that are coupled with the intention but anticipating it. The subclass of motor anticipatory interfaces exploits any involuntary motor behaviour of the user that anticipates the intended command.

Involuntary movements do not impose any cognitive load to users as they form an integral part of the related sensory-motor task. There is a wide group of known involuntary movements that anticipate the related motor intentions [39], such as gaze and head movements which contain most of the information on human desired actions. They can be tracked by a multitude of devices such as gaze tracking systems, inertial measuring units, and optokinetic/photogrammetric/ultrasound apparatus for movement analysis. The only class of anticipatory movements that was exploited in the very first prototype of anticipatory interface is the head rotation anticipating the steering action during active locomotion [40, 41]. This movement was chosen due to its wide anticipatory time (approx 1 s) and easy to detect rotation (approx. 25-30), as showed in Figure 3, taken from [40]. The interface is potentially able to drastically reduce the communication delays in teleoperation tasks (compare Figure 4 and Figure 5). Although research on anticipatory interfaces is only at the beginning, their potential for space application is apparent.

Liquid Ventilation and Water Immersion

Motivation

The presence of human beings inside of moving machines in general greatly limits the variety of manoeuvers the machine can take in order not to harm the fragile human body. In airfighters, pilots wear special suits to compensate momentarily appearing

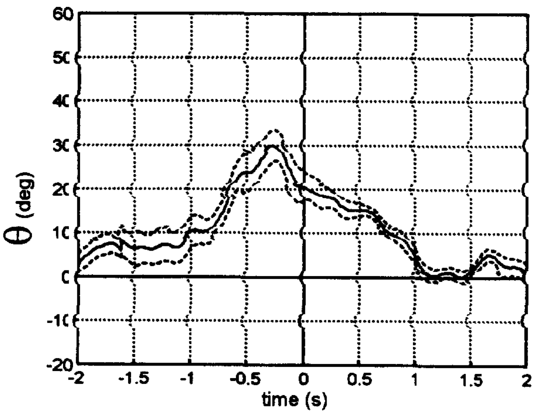

Figure 3: Head anticipatory movement during walking steering. Steering begins at time 0. The wide anticipatory rotation is apparent, as well as the re-alignment of head after steering. [40]

acceleration (see below), in manned spacecraft, the control architecture is far more complex than in unmanned ones. Overcoming the physical fragility of the human body would allow for maneuvers at much higher G levels, and hence would allow for previously unthinkable mission concepts.

The human body consists of different parts with different specific weight. When subjected to accelerations, each of these elements experiences a relative change in weight compared to the other body elements. This effect is particularly pronounced with the skeletal system and the fluidic components, which have the highest density values in human body. While the musculo-skeletal system is firmly linked, the fluidic components are indeed surrounded by soft tissue. Hydrostatic pressure changes result in shifts of the fluids and deformation, with expansion of surrounding tissues [42, 43]. For example, under headwards (+Gz) acceleration the inertial response is directed footwards, then blood pools in the splanchnic region and in the superficial vessels of the lower extremities. The cardiac return is decreased which then also reduces the heart's filling and its subsequent arterial outflow and pressure of the next beat. It becomes increasingly difficult for the heart muscle to maintain arterial blood circulation at the level of the eyes and brain. If these conditions are prolonged for more than three to five seconds, insufficient oxygen and

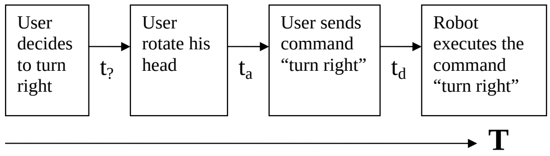

Figure 4: Functioning time line of a standard control interface with an intrinsic communication/execution delay present (t_d). The time elapsed from the user first intention to the execution of the command is equal to the sum of the time between intention and anticipatory movement ($t_?$ - ingored), the time between anticipatory movement and the intended movement (t_a - anticipation), and the intrinsic time delay (t_d - delay).

electrolyte supply occurs, resulting in lack of vision, and, after few more seconds, loss of consciousness [44]. At this stage, if the acceleration is not immediatly reduced, firstly irreversible brain damages, and subsequent death, will follow.

Figure 6, taken from [44], illustrates the hydrostatic pressure differences in the systemic and pulmonary circulations of a seated pilot at 1 Gz (centre panel) and at 5 Gz (right panel). Supposing that blood pressure imposed by the heart pumping does not change, just at +5Gz blood pressure at head level is already reduced to zero, clearly showing that without any countermeasures, each subject would experience the above described symptoms.

Anti G Suits

More than 70 years ago the development of anti-G suits was initiated in order to reduce the probability of in-flight incidents related to the loss of consciousness phenomena and its often fatal consequences, [45, 46, 47, 48]. These devices apply counter-pressures to the lower extremities and abdominal region, preventing blood from pooling in these regions. By using these suits in combination with special respiratory straining techniques, pilots can sustain Gz values of up to 9 G. A rather simple approach to facilitate blood reflux during prolonged phases of acceleration is to simply orient the long axis of the body perpendicularly to the thrust of acceleration, most suitably with the subject in the supine or prone position [49, 43]. In such an orien-

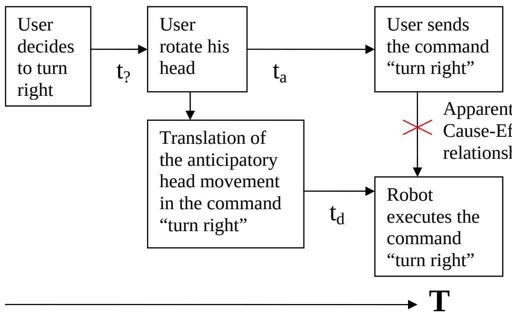

Figure 5: Functioning timeline of an anticipatory interface with an intrinsic communication/execution delay present (t_d). The time elapsed from the user first intention to the execution of the command is equal to the sum of the time between intention and anticipatory movement ($t_?$ - ignored), and the intrinsic time delay (t_d). The timeline has been shortened from the anticipation time. If the delay between the translation of user intention from its anticipatory behaviour and the execution of the intended command is set to be equal to that of natural anticipation (t_a), the user experiences an apparent cause-effect relationship between its interface operation and the corrisponding command execution

tation, the maximum intravascular pressure developed under transverse acceleration is considerably less than it would be under longitudinal acceleration, since the anterior-posterior dimension of the body is only of a small fraction of the sitting height. But this technique is not free of side effects: in the horizontal supine position, the heart is abruptly displaced in dorsal direction and hence threatens the lungs with severe over-distension which may lead to lung injury [50].

Water immersion to overcome the effects of acceleration

Once completely immersed in a physiological water solution within a non expandable container, human beings are able to sustain acceleration with a magnitude of 24 Gx without any noticeable pain; or in other words the double of the acceleration which usually causes strong pain, unfeasibility of breath-

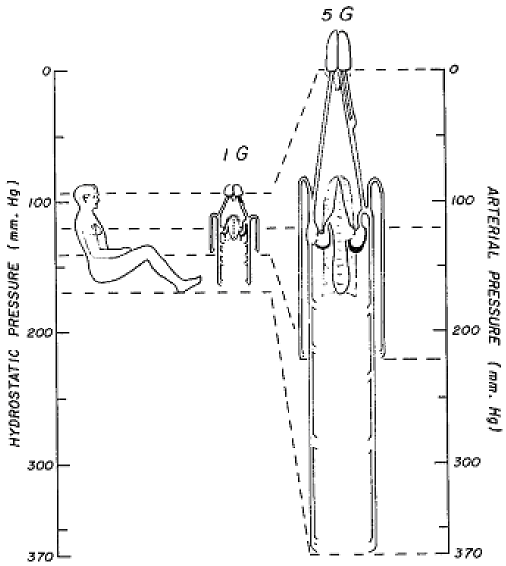

Figure 6: Hydrostatic pressure differences in the systemic and pulmonary circulations of a seated pilot at 1 Gz (centre panel) and at 5 Gz (right panel). Already at +5Gz, blood pressure is reduced to zero at head level. Physiological countermeasures are not taken into account. Taken from [44]

ing, and after few seconds the phenomena of grayout, blackout and unconsciousness [44]. Water immersion augments tolerance to acceleration as the acceleration forces are equally distributed over the surface of the submerged body [46]. This abruptly reduces the magnitude of localized forces and a homogenous hydrostatic response of the whole body is induced. The increased fluid pressure developed within the cardiovascular system during acceleration is approximately balanced or even cancelled out by the gradient of pressure developed in the liquid tank outside the body [51, 52], with evident benefits for blood and lymphatic circulation.

The first limiting factor for acceleration tolerance under water immersion appears to be the related thoracic compression [53, 54, 55, 56, 51, 52]. The thorax, with its air-filled lungs, has a mean density considerably lower than that of the rest of the body which results, when accelerated during water immersion, in orthogonal homogeneous thoracic squeezing. This compression causes severe difficulties from pain, lung hemorrhage, pneumothorax, alveolar collapse, to even death depending on the magnitude of acceleration. Besides, in order to breathe under exposition to the elevated extra-thoracic pressure, the inhalating gas has to be over pressurized. This procedure produces the typical scuba diving issues, related with the high level of nitrogen solved in blood which induces alterations in behaviour and consciousness, reduction of intellective properties, ammonia intoxication and embolism.

If, however, the air is removed from the lungs, the sustainability to linear acceleration reportedly increases significantly [55, 56]. Animal studies with mice showed that, where the acceleration-time lethal threshold for water immersed mice is around 1300 Gx for 15 seconds, when their lungs are emptied from air, the maximum acceleration reaches 3800 Gx for more than 15 minutes without any physical impairment.

The current technique for achieving respiration with air-free lungs is the extracorporeal circulation. While it is an approved method commonly applied in surgical operations such as open heart surgeries, the extracorporeal circulation is complex to manage, and imposes the administration of anticoagulant drugs in high doses. To improve acceleration tolerance, it seems too risky, difficult and complex as procedure to be practically implemented for space applications.

Oxygen supply for immersed astronauts

If it is not possible to empty the lungs, there is still the option of filling them with another liquid: experiments showed that, during water immersion, the liquid inside the lungs reacts to pressures produced by any accelerations with an equal hydrostatic pressure, and directed in the opposite direction, counterbalancing the thoracic squeezing, and avoiding pain and difficulties to breathe [57]. It is also possible to breathe liquid instead of air by filling the lungs with a specially prepared fluid in which both respiratory gases oxygen and carbon dioxide are highly soluble [58, 59, 60, 61]. The perfluorocarbon (PFC), a liquid carrier medium for gas exchange, has been demonstrated to be free of negative side-effects for both short and long term use, and to be easily removable from alveolar sacs. Under such circumstances, it can be expected to increase the current 24 Gx limit of human tolerance during water immersion. Direct theoretical and experimental data on humans supporting these assumptions are however still lacking.

Furthermore, liquid ventilation faces some technological challenges that make it, for the time being, not yet applicable in humans. The currently biggest show-stopper appears to be the PFC liquid itself which has to be oxygenated and freed from carbon dioxide at least four times per minute [62]. As the high density of this liquid makes it impossible to be breathed naturally, PFC has to be mechanically exchanged continuously, which is more problematic than conventional gas ventilation [60]. The adjustment and regulation of expiratory or inspiratory pressures has to be finely tuned as liquids - contrary to gasses - are far less compressible. Any slight overpressure would charge the lung tissues and seriously threaten their integrity. At the current state, only prototypes of liquid ventilators for small animals exist and human experiments are not foreseen [63].

Conclusions

A number of concepts that could substantially change the way we approach the design of human solar system exploration in a far fetched future are being studied. This papers intends to present the status of some of these concepts: human hibernation for long duration interplanetary travels, machines interfacing directly to the astronauts brains or to their involuntary reflexes, astronauts immersed in a thin water layer surrounding uniformly their bodies, whilst they are breathing liquid instead of air.

Even if so far hibernation has not been induced yet in mammals belonging to non hibernating families, artificially induced hibernation has been achieved using the chemical compound DADLE. Before evaluating the real potential of inducing hypometabolic states in human, more scientific results on the effects of microgravity on hibernating beings are needed. If the protective mechanisms of hibernators concerning physiological atrophy during torpor will prove to be effective also during microgravity conditions, hypometabolic states during space flight could become an option to approach physiological and psychological stress of crew members. But it can also well be that the presence of microgravity adds other insurmountable problems unless artificial gravity can be provided at reasonable cost. So far there is no theoretical model and hence only experimental data on animals hibernating under microgravity conditions, as planned by the Canadian Arrow Project, will elucidate the feasibility of the proposed techniques.

The benefits of neuroinspired interfaces for space applications could also be significant, allowing astronauts to operate in an 'unnatural' environment without handicaps and to reduce the communication delay during robots teleoperations. Based on current scientific knowledge and progress, a dedicated MEG-BMI module might be the method of choice in the far future. For immediate implementation trials of space dedicated BMIs, the EEG-BMI platforms seem to be the only practical solutions, due to their technical simplicity and portability. Moreover, an EEG-BMI system could be a good testing platform for a number of studies on the modifications of brain activity caused by microgravity exposition.

Finally, liquid ventilation has been assessed. Liquid ventilation is a well developed technolgy. Premature infants are already treated with a partial filling of the lungs with PFC and the other half with atmospheric air, and prototypes of total ventilators for animals have already been realized. As a consequence, an application on adult humans can be expected in the near future.This technology will allow the design of liquid-filled capsules for astronauts, inside which the stress experienced during high-G acceleration will be reduced to the hydrostatic pressure gradient all long the acceleration axis and a homogeneous hydrostatic pressure that depends on the thickness of the layer of liquid water surrounding the astronaut. Using a liquid film of only one centimetre thickness between subject and shell, the hydrostatic pressure would reach values close to zero and the only stress experienced should be that caused by the pressure gradient.

It is difficult to estimate an ultimate acceleration limit possible with this set-up, but it presumably can be higher than hundreds of G. The weight associated to such a liquid shock absorber would scale considerably with the amount of liquid required. Nevertheless it would allow the spacecraft to undergo far higher accelerations and hence, possibly, for a simpler design that could overcompensate the weight of the liquid ventilator. Completely new concepts, such as magnetic railguns, could also be considered for manned missions, should it be experimentally confirmed that the physiological stresses due to high acceleration loads vanish using this type of set-up. Most of the components of such a systems have already been realized, the development of experimental demonstrators with animals could be initiated right away.

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