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Space travel in a high-altitude environment: One more step in human BioSpaceForming

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Abstract:

BACKGROUND: Currently, space programs use sea-level pressures (760 mmHg) and normoxia (21% oxygen fraction) in space capsules. When astronauts need to go for a spacewalk, the pressure has to be reduced to 1/3 that of sea level (240 mmHg). This implies that in order to avoid decompression sickness (DCS) and acute mountain sickness (AMS), complex and time-consuming procedures need to be carried out. Furthermore, space suits have to sustain such pressure and protect them from radiation. A cooling vest is also used in order to keep the body temperature within normal values. This makes the space suits very voluminous and hence with rigid structures in order to sustain the pressure in space. Astronauts suffer, among many other complex microgravity alterations, anemia, that upon return to sea level, has to be correspondingly normalized to preflight levels. The reason that anemia presents is in part due to a lower requirement of oxygen by orthostatic muscles in microgravity. Exercise in space, reduces bone and muscle wasting. Over 200 million high-altitude residents live above 2000 m (6560 ft) of altitude and have adapted perfectly to life in the mountains. They live their life as if they were at sea level. They reproduce and practice sports, all this with a higher hematocrit. They even have proved extended longevity.

METHODS: The knowledge acquired during 47 years of medical practice at high altitude, is applied to a proposal for a most efficient capsule environment for the human exploration of space.

RESULTS: A cabin pressure similar to the city of La Paz, Bolivia (495 mmHg), that is, 2/3 that of sea level (760 mmHg) would not only maintain the hematocrit for reentry, but furthermore, could significantly accelerate the preparation for extravehicular activity that currently takes up several hours. High-altitude residents can tolerate lower levels of oxygen (hypoxia) providing them with an advantage of survival in oxygen poor environments. We likewise propose that a lower pressure (149 mmHg) be used in space suits, making them more flexible and thereby reducing the risks of DCS and AMS. This implies only 346 mmHg in pressure difference, from space capsule to space suit, as compared to 520 mmHg in the current methodology.

CONCLUSIONS: The laws of physics in relation to pressure changes cannot be broken. However, human biology with adaptation to lower pressures and lower levels of oxygen and carbon dioxide, which is the case of high-altitude residents, can reduce the pressure gap significantly. Thereby, biology breaks the limitations of the laws of physics. Space travel will always have hypoxia as a fundamental threat, hence a hypobaric, normoxic space capsule environment results beneficial, practical, and one more step in "BioSpaceForming" of human beings.

Keywords:

Adaptation, chronic hypoxia, high altitude, space travel, tolerance to hypoxia

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Planet Earth, inhabited by human beings along with animals, plants, microorganisms, and others, has an atmosphere (Troposphere) that extends to approximately 17 km of altitude. The gas surrounding Earth is composed of 20.93% oxygen, 78.9% nitrogen, 0.03% CO_2, helium, and others. Atmospheric pressure decreases

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exponentially with altitude because there is more density of molecules at the base of the atmosphere, due to the weight of all those molecules attracted to earth by gravity. Humans have adapted not only to sea level but also to cities like La Paz, located at an altitude ranging from 4100 m (13,450 ft) 3100 m (10170 ft).[1] Over 200 million people live above 2000 m (6560 ft) of altitude around the globe.[2] However, adaptation can also possibly extend to the highest point on Earth, Mount Everest (8842 m), under special circumstances.[3] Living beings require oxygen for survival, an element abundant here on Earth but very scarce or nonexisting on other planets. Initial space flights were carried out, in a pure oxygen environment (100%) and 1/3 the sea-level pressure (240 mmHg). It was thought, at the time, that oxygan used along with the in-flight pressure reduction diminished the risk of decompression sickness (DCS) (known as "the bends").This resulted in a tragic accident and immediate death of 3 astronauts on Apollo 1, before takeoff.[4] It was then decided that cabin pressure and oxygen concentration should be the same as at sea level. This concept still prevails today on all space vehicles.

PB = 760 mmHg

Oxyge*n* = 21%

$PIO_2 = 150$ mmHg

Where PB = Barometric pressure and PIO_2 is the inspired oxygen pressure at sea level.

Currently, in order for astronauts to exit the spaceship for extravehicular activities (EVAs), the pressure has to be reduced, in a complex and time-consuming procedure, to 1/3 that of sea level. This pressure of 240 mmHg is comparable to that on the summit of the Mount Everest. Special fabrics are used in order to provide body flexibility within the space suits, maintaining this pressure in the absence of pressure in space. However, this makes them voluminous and rigid, thereby limiting the maneuverability of the EVA suits.

The astronauts' suits have to be extensively tested for efficiency.[5] Several important variables have to be managed: the pressure container around the astronaut, protection from extreme environmental hazards (radiation, micrometeorites), human performance (mobility, workload), flexibility and functionality of the gloves,[6] and thermal control.[7] One of the primary concerns of lowering the pressure for the moon walks was the risk of suffering acute mountain sickness (AMS).[8]

Astronaut's spacesuits and life support systems currently contain a high-flow circulating system, whereby the breathing gases pressurize the suit and provide supposedly adequate oxygen levels along with thermal comfort. The mixture is about 100% oxygen at about a 1/3 of sea-level atmosphere pressure.[9] In other words, this 1/3 of the sea-level pressure (760 mmHg) is 253 mmHg. If 100% oxygen is utilized, this would correspond to PIO_2 of 206 mmHg, provided the water vapor pressure (47 mmHg) at body temperature (37°C) would be subtracted. This means that if sea-level PIO_2 is equal to a 150 mmHg, there is an extra 56 mmHg which is actually hyperoxia. The authors do not quite understand the reason for this gas pressure. Perhaps, it is meant to provide the astronauts more oxygen, based on the idea of giving them extra energy, or avoiding to carry nitrogen tanks. However, nitrogen is fundamental in order to maintain alveolar surface tension and should not be discarded.

There are several publications where there is variation in the actual pressures of the cabin and the EVA suits. Some affirm that in the space shuttle, the cabin pressure is reduced from the normal 760 mmHg to 500 mmHg (2/3) only before EVA. Then, in the airlock, it is reduced to 250 mmHg (1/3). Likewise, it has been established that during the decompression and recompression procedures, the rate of change should be 0.007 bar/s. During emergencies, this recompression rate could be further increased to 0.07 bar/s. Furthermore, these procedures using sea-level cabin pressure require that the astronaut breathe 100% oxygen, 1 h before and then decrease the shuttle cabin pressure from 760 mmHg to 500 mmHg. Subsequently, they don their EVA suits and breathe 100% oxygen during an extra 40 min. Finally, in the airlock, the pressure is reduced to 250 mmHg.[10] All pressure units expressed in that paper are in bars, however, for the sake of clarity they are converted to mmHg in this paper.

During space flight, bone and muscle loss occurs fundamentally during the first 5 months. This is the process of adaptation to microgravity in space.[11] Applying the concept of our Adaptation to high altitude formula,[12] we infer:

Adaptation = time/space bone loss

Although this may seem speculative, it is rather based on physiological laws of adaptation that are universal and refer to every type of tissue in different environments.[13] Upon returning to Earth, the full recovery of the pelvic bone takes a little over 1 year. This can be explained because the space loss of bone is a destructive process and runs faster than the reconstructive process. Whereas upon return to sea level, the reconstructive process of pelvic bones and possibly all other bones, takes almost twice as long.[14,15] This, as expected, has to follow the concept of adaptation as expressed in the adaptation formula to high altitude:

Adaptation = time/altitude

Going from sea level to an altitude of 3600 m (11,800 ft) in the city of La Paz, Bolivia, it takes 40 days for the red blood cells, hematocrit, and hemoglobin to increase to their optimal plateau level, being this the fundamental process of adaptation. Whereas, on descent to sea level, it takes only 20 days to decrease to the optimal level in a linear way (1/2 the time) as a form of readaptation, being nevertheless still an adaptation.[12,16] As referred by the late Prof. Dr. Gustavo Zubieta-Castillo, he strongly affirmed that adaptation is a permanent process. He firmly opposed the use of the term "loss of adaptation" or "de-adaptation." These two last terms were totally unacceptable to him as he affirmed that the organisms are constantly adapting. He affirmed: "The organic systems of human beings and all other species tend to adapt to any environmental change and circumstance within an optimal period of time and never tend toward regression which would inevitably lead to death."[17]

Over time, the increase in the number of red blood cells, hematocrit, and hemoglobin is the optimal and most energy efficient adaptation method in order to liberate the heart and the lung from excessive work.[18] During space flights one of the complications of astronauts is anemia with the mechanism explained by neocytolisys according to some authors,[19] but also attributed to a diminished use of muscles such as the legs and other orthostatic muscles, due to microgravity.[1]

Some authors are proposing lower pressures to reduce the prebreathing time to 15 min, to minimize the risk of DCS.[20] The first author has originally proposed these concepts in 2007.[1] Posteriorly, in 2010, during the Chronic Hypoxia Symposium III, he published as an abstract,[21] the use of a lower cabin pressure in space vehicles with the idea of reducing the risk of DCS and facilitating the construction of more flexible EVA suits. This paper further advances and details such proposal. Previously, the authors, in 2006, have proposed that launching space vehicles from high-altitude sites like at 4000 m in the Bolivian Altiplano (high plateau) would give rise to evident advantages like saving energy during the scape from the gravitational pull.[22] These concepts were presented in talks, at BLDE University Engineering School in Vijayapur, India in November 2017, also in April 2018, at the National Institutes of Health in Bethesda, Maryland, also at the Center for Space and Planetary Sciences of the University of Arkansas in Fayetteville and likewise at Tulane Medical School in New Orleans, Louisiana, in the Physiology Department under the direction of Luis Gabriel Navar.

DCS is a risk concerning the lowering of the pressure in the environment and thereby creating nitrogen bubbles in the bloodstream and different tissues of the body. In water, the changes are more severe, and the risk of suffering DCS is much greater during diving. Some authors have suggested using a hypobaric gas atmosphere in space cabin and/or planetary habitat, substituting nitrogen in a normobaric gas atmosphere with another inert gas (helium and neon) as countermeasures against DCS in EVA crewmembers.[23] Space suits with new technology have to be low weight, highly flexible, and with a low risk of DCS.[24] The Russian Orlan spacesuit with a pressure of 40 kPa (300 mmHg) and a 30 min oxygen prebreathe protocol has not had any incidences of DCS in 78 EVAs in the MIR station.[25] The Russian protocols for EVA have shorter prebreathing times and also have higher pressure in their suit which they believe reduce the risk of DCS.[26]

No ventilation/perfusion (VA/Q) anomaly in the lungs has been found during the decompression procedures for EVA in the international space station in eight subjects studied with the existing protocols, which confirms the adequate prebreathing times.[27] No significance differences to space flight adaptation has been found between genders, except for an orthostatic presyncope intolerance in women.[28] Peak maximal oxygen consumption (peak VO2) in astronauts has been shown to decrease during spaceflight and full recovery is achieved 30 days after their return.[29]

Recently, a study of two twins showed that one of them, the astronaut that remained in space for 1 year, presented a change in 7% of his genes in comparison to his earth resident twin. These changes were attributed partly to radiation, calorie restriction, hypoxic stress, and possibly hypercapnia (an increase of CO_2). Concomitantly, there were increased inflammation markers and dramatic nutrient shifts. There also was mitochondrial stress and increased levels of mitochondria in the blood.[30] The authors believe that hypoxia was not the fundamental cause of these changes, because we would see similar changes in chronic hypoxia high altitude residents. Unless, there were several episodes of acute severe hypoxia. Perhaps, a twin study between one residing at high altitude and the twin brother at sea level, could clarify this point.

Some authors have considered the realistic approach to modifying the atmosphere of missions to Moon and Mars.[31] This paper proposes a change in the environmental pressures in space vehicles and space suits in order to provide a better quality of life for astronauts in the venture of space travel.

Theory and Calculations

The logic behind this proposal, is that if the environmental sea-level pressure (760 mmHg) in the space vehicles is permanently reduced to 2/3 less (495 mmHg), equivalent to that of the city of La Paz, Bolivia, located at an average altitude of 3600 m (11,600 ft) within the Andes, then space travel can be more efficient.

The current pressure in the environment of the space vehicles is sea-level pressure. Table 1 shows the current pressure and the proposed pressure change.

The pressure in the extravehicular mobility unit currently and that of the proposal are shown in Table 2.

If we increase the FIO_2, in our proposal [right column in Table 1], to 63%, maintaining the same PIO_2 of 94 mmHg which corresponds to an altitude of 3600 m on planet earth, then we are able to reduce the pressure inside the suit much more to 149 mmHg [Figure 1], according to the following formula:

$$\text{EVA pressure} = (PIO_2/FIO_2) \times 100$$

where FIO_2 is the Fractional Inspired Oxygen Tension. The PIO_2 is maintained at 94 mmHg, again, the suitable physiological pressure of the air inspired by the inhabitants, at 3600 m of altitude.

This implies that there is an economy of the suit's pressure of 91 mmHg with respect to the current pressures used. This has fundamental implications because the suits can be made to resist less pressure and consequently be lighter and much more flexible, with thinner fabrics. The more we reduce the pressure without risking the life of the astronauts, the more comfort they will have. We will approach in space to what our skin is to humans, on planet earth.

Table 1: Intravehicular pressures and oxygen percentages in space travel with sea level pressure and that of the city of La Paz, Bolivia

	Currently (sea level)	Our proposal (3600 m)
Barometric pressure	760 mmHg	495 mmHg
Percentage of oxygen	21	21
PIO2	150 mmHg	94 mmHg

PIO_2=Partial pressure of inspired oxygen

So the question is: what is the limit of tolerance of low pressure within the suit that does not put the astronaut's life in peril? One could start analyzing the boiling temperature of water. What is the lowest pressure at which water would boil in space? The water boiling point reduces with increasing altitude. At sea level, it boils at 100°C (760 mmHg). Since the human body is at 37°C at an extremely low pressure, there is the risk that its fluids would boil at the level of the mouth. The water vapor pressure at 37°C is 47 mmHg. At the altitude of 3600 m (11,600 ft) in the city of La Paz, water boils at 88°C. At 9000 m (29,500 ft) of altitude, water boils at 72°C. Hence, in theory, humans could tolerate a pressure above 47 mmHg, which would be the critical point. This corresponds roughly to 19,000 m of altitude. However, one has to have a margin of security since the body could have an increase of its temperature due to factors such as fever, performing exercise, or cooling system malfunction. Fast decompression to 0 gravity in space gives rise to ebullism ("boiling away" of water

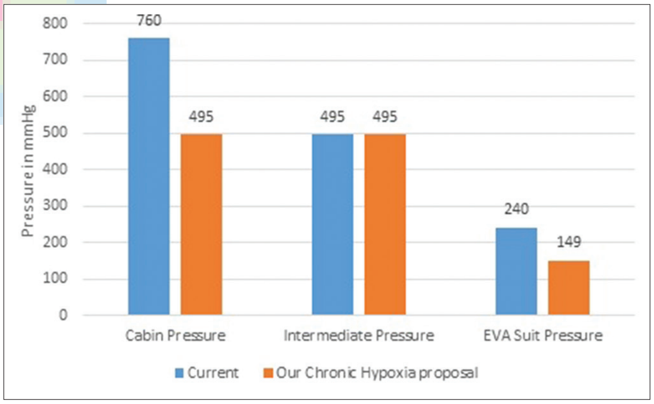

Figure 1: The current pressures used in the cabin and in the transition to the use of the extravehicular activity Suit and the proposal of this paper. Note that there is no intermediate stage, which accelerates and facilitates extravehicular activity. Nevertheless, an intermediate pressure of around 322 mmHg could be applied

Table 2: Characteristics of the extravehicular activity (EVA) suit breathing air at the Lower PIO2 and increasing the FIO_2 from 55% to 63%. The FIO_2 of the EVA suit, has to be increased fron 21% to 55% in order to achieve the pressure of PIO_2 = 99mmhg at 1/3 the pressure of the space ship

	Currently used (sea level) in mmHg	Our proposal (3600 m) in mmHg	Our proposal (3600 m) in mmHg
FIO_2 (%)	63	55	63
PIO_2	153	94	94
PCO_2 in mmHg	40	30	30
Water vapor pressure (37°C)	47	47	47
Total Minimum pressure in EVA	240	171	149

PIO_2=Partial pressure of inspired oxygen vapor from the body) that comes on exposure to lower than 47 mmHg.[32]

Discussion

The fundamental value that cannot be reduced is the PIO_2 of 94 mmHg that of the city of La Paz. As long as we maintain this pressure, the organism will receive enough oxygen for its perfect function, provided there is a previous gradual adaptation. This could be achieved by living in the city like La Paz for at least 40 days before travel or in a simulated hypoxic environment.[12] Or likewise, on long space flights, the pressure could gradually be reduced from that of sea level to that of the city of La Paz. Consequently, if we give 100% oxygen (instead of the 63% FIO_2, shown above as calculated with the formula in Table 2), in theory, we could use a suit pressure of as low as 94 mmHg. However, the water vapor pressure has to be included, hence a 94 mmHg + 47 mmHg = 141 mmHg. Nevertheless, the water vapor pressure would not be 47 mmHg as the skin temperature is around 25°C, except at the level of the mouth or the eyes, where it would be 37°C. CO_2 exhaled is also reduced from 40 mmHg at sea level to 30 mmHg at 3600 m, however, it would not exert significant pressure, as it would be rapidly absorbed in the high flow circulating system.

AMS is not an issue at any moment during this flight, as the astronauts are using the high altitude normal PIO_2. DCS could perhaps be an issue, however, the authors believe that at this pressure changes, it only corresponds to a dive in water of around 5 meters (495 mmHg–149 mmHg = 346 mmHg, less than half an atmosphere). High-altitude lake diving can pose special risks, but this is for deeper dives. We have developed high-altitude diving tables online.[33] In space, if a pressure of 149 mmHg is used, the prebreathing of 100% oxygen before pressure reduction will avoid any risk of DCS, as currently used. This low pressure along with the "Bioformin" of space travelers thanks to adaptation to chronic hypoxia, a normal earth high-altitude circumstance, would grant advantages in the physics of pressures. Physical laws cannot be altered in space. Human organisms can adapt safely to a lower oxygen pressure without putting at risk the physiological survival. This would imply a biological advantage surpassing pressure differences, whereby Biology transforms Physics limitations. In this regard, we propose a most adequate term which is the following: "BioSpaceForming". It is remarkable that upon return to sea level, this temporary and functional adaptation could be reverted to sea-level values.

Since this would be an extremely low pressure, the EVA suits could be very flexible. Therefore, a suit pressure of 149 mmHg [Table 1] seems very feasible and perhaps one could explore the possibility of further reducing it to an extreme of 94 mmHg, breathing 100% oxygen, and providing extremely flexible suits. As stated above, astronauts have lower oxygen consumption in space, and this is a natural adaptation that favors the proposal, herein made. This, of course, needs adequate research and testing. Furthermore, it seems evident, that human beings can adapt to even higher altitudes on planet earth,[34] which would lead to the reduction of environmental pressure, in future space travel, achieving extreme low pressures, and outstanding survival levels. Paraphrasing, Neil Armstrong, the first astronaut to step on the moon, "one giant leap" in the venture of human beings beyond planet earth.

Within space, the barometric pressure is near 0 mmHg. High-altitude residents in the city of La Paz live, because of their circumstances, closer to space at 1/3 less barometric pressure than sea-level residents. These inhabitants are perfectly adapted to life with these pressures. Oxygen is abundant in our planet but scarce in space. Humans living at high altitude are more tolerant to hypoxia,[35] tolerating six times greater hypoxia at the summit of Mt. Everest, than at sea level. Life under chronic hypoxia benefits in many ways and one of them is even extended longevity.[36] Paradoxically, there is more tolerance to hypoxia, the higher one goes. In reality, sea-level residents have one crucial disability: poor tolerance to hypoxia.

For a sea-level resident, the high altitude of the city of La Paz (3600 m) seems complex and sometimes, based on general comments, as something intolerable. This is definitely not true. Hundreds of thousands of visitors arrive in El Alto airport at 4100 m. The High Altitude Pulmonary and Pathology Institute has been treating some people that have suffered AMS for over 48 years (as of 2018). We have seen very few cases of High Altitude Pulmonary Edema and High Altitude Cerebral Edema and they have all evolved favorably without the need to go down. No deaths due to exposure to hypoxia have been encountered, although they have been reported outside of our Institute, when inadequate medical care was provided without the suitable resources and the knowhow. Many diplomats and entrepreneurs in La Paz composed of thousands of sea-level residents carry out normal lives. This implies that it is perfectly possible for sea-level residents to adapt to a normal life at high altitude. In fact, many visitors find that their health conditions improved at high altitude, as is the case of anemia, asthma, and cardiovascular diseases. Hence, most healthy sea-level residents can perform and live at high altitude, as though they were at sea level. They adapt and live all their lives perfectly well. Consequently, this innovative proposal is totally feasible for sea-level astronauts, provided they follow an adequate adaptation strategy.

If there is anything mankind will have to face in space, it is hypoxia and this can be the greatest threat to survival. With our extensive experience in high-altitude medicine in our institution, the High Altitude Pulmonary and Pathology Institute (IPPA), we propose a complete change of attitude in the general way of thinking: Stop fearing hypoxia and instead, take advantage of it. Humans will have to adapt to hypoxia in order to become an interplanetary species.

Conclusion

High-altitude residents have a good quality of life in cities such as La Paz and El Alto (3100 m–4100 m). Practically, all residents are unaware that they are living in chronic hypoxia. Several cardiovascular diseases, obesity, and other pathologies such as asthma and cancer have a lower incidence at high altitude. Not surprisingly, high-altitude residents have extended longevity in such environments. With all this knowledge and experience, we propose that space vehicles have 2/3 the pressure of sea level (495 mmHg) with a PIO$_2$ of 94 mmHg. The adaptation process, following the high-altitude adaptation formula,[12] will grant astronauts an increase of red cells, reducing the problem of space flight anemia, and providing them a higher tolerance to hypoxia.[35] The lower pressure on space suits of 149 mmHg with 63% FIO$_2$ maintaining a PIO$_2$ of 94 mmHg, simulating the altitude of La Paz, will allow for much more flexible space suits and lower preparation times with a reduced risk of DCS and practically no AMS. Further research into this concept is fundamental in order to advance. Science and the knowledge of hypoxia will lead human beings to their inevitable destiny: life in space, within the universe.

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Conflicts of interest

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