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Numerical simulation of long-term microgravity effects on the cardiovascular system. Validation and Results for Moon and Mars exploration scenarios.

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Introduction

We report on the results and validation of the model NELME (Numerical Emulation of Long-Term Microgravity Effect) across a wide variety of altered gravity scenarios. Computer simulations have become increasingly available tools for making predictions on the outcomes of complex physiological systems in extreme environments. However, technical limitations and difficulties of finding out opportunities to produce large series of experimental data to validate the models have made it difficult for these models to become available. In the recent years, this situation has changed as supercomputer facilities have increased their power; and more experimental data from parabolic flights and other altered gravity platforms are available to researchers as well. Results are provided about different simulations that have been conducted for short, medium-term and long exposures to microgravity; along with different events embedded. These simulations may include simulation of physical aerobic exercise during a mission, EVAs, thermal stress or human exposure to altered gravity scenarios (centrifuges, Martian or Lunar gravity, rocket launch, etc.). Risks for human health that may put in jeopardy a manned space mission in a variety of scenarios are evaluated and discussed.

1. Development and validation

Details on the development of NELME model are provided, a computer electrical-like physiological model which takes into account variables such as gender, weight, height and also environmental variables like temperature or exposure to gravity. From the model, we can retrieve output results related to the cardiovascular performance under stress and/or exposure to altered gravity. These measurements lead to an assessment of the deconditioning of the cardiovascular system in different scenarios. This is of interest, for example, in cases where it is unlikely that animal models or humans can be experimentally tested, such as long-term exposure to microgravity. The model has been validated through parabolic flights conducted at the Barcelona-Sabadell Airport using an aerobatic aircraft CAP10B. This aircraft is capable of providing parabolas of up to 8 seconds of microgravity preceded and followed by peaks of around 2 seconds of hypergravity (Perez-Poch et al. 2016). Experimental validation of the model in parabolic flight includes 5 different subject included in the sample. The model, once it has been validated, is intended to be applied to investigate on exposure of human exposure to different altered gravity scenarios.

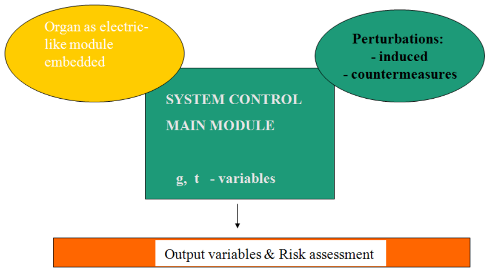

Figure 1: Modular concept of NELME software analyzer.

Initial validation was performed by applying the Runge-Kutta equations model on orthostatic intolerance by Heldt (Heldt et al. 2002) and comparing the results from this former model to that obtained in the electrical-like model simulation of our software. Results for the change in Arterial pressure (mmHg.), Mean heart rate (beats/min.) and Mean Stroke Volume are compatible with less than 10% error ($p<0,05$).

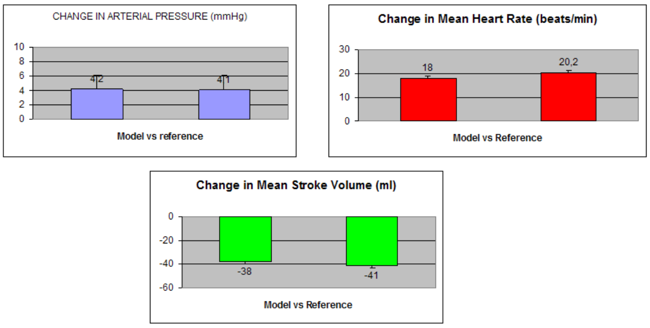

Figure 2: Initial validation of the NELME model implementation.

2. Simulation results

Results from the simulations account for a degree of impairment of human capabilities which may be of interest for designing future long-term human missions to Mars or other destinations. Interestingly, a long-time exposure to less than 0.35g seems to be as hazardous as a zero g for missions longer than three months, when we analyze the Vascular Resistance deconditioning (%, $p<0,05$) whereas aerobic exposure does not fully counteract the risks.

Aerobic exercise as countermeasure can also be studied in simulation, as we can model the induced physiological stress with an electrical-like analogy in the circuit model. Different patterns of exercise can be introduced in the former simulations, with different time and intensity protocolos. Then, risk reduction for the entire mission can be evaluated by using current standard procedures (Stamelatos & Dezmull 2011).

Furthermore, it is well known that the most stressfull episodes in a manned space mission are the Extra Vehicular Activities (EVAs). We can also estimate the risk estimated with these demanding activities in terms of how they stress the cardiovascular system, taking into account both temperature increase, anaerobic and aerobic exercise.

We have then applied all these events into a full mission scenario to Mars and Moon, taking into account the different gravity loads involved in different parts of their mission, including a prolonged stay on the planets.

Some results from Moon missions risk estimation are shown in Figure 3.

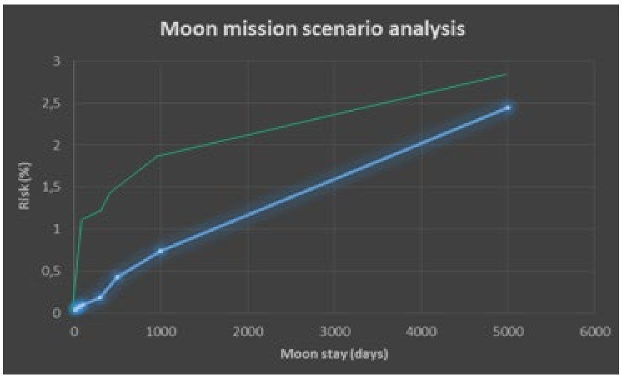

Figure 3: Moon mission scenario analysis risk estimation (green: with 1/week EVA)

A nearly linear increase appears between the associated risk with microgravity and lunar gravity exposure. However, the risks are within currently accepted limits of putting a mission into jeopardy. Aerobic exercise is fully accounted in this estimation, and, also in the line in green above, it can be seen the increase of the risk with a protocol of EVAs of no more than once per week.

We proceed in an analog way with Mars Mission scenarios, including a prolonged Mars stay on the planet, and a travel back to Earth (Figure 4).

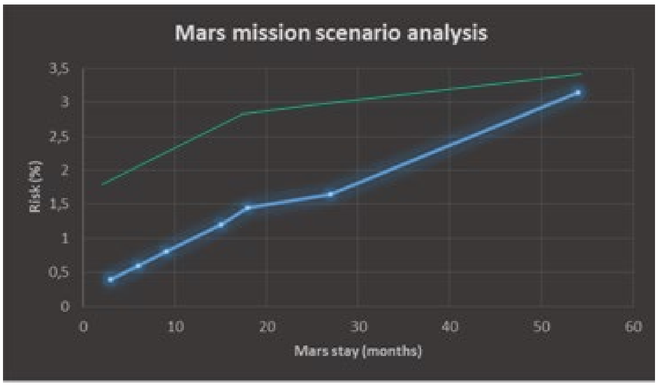

Figure 4: Mars mission scenario analysis risk estimation (green: with EVAs)

The final results are shown in blue line, and in green with the same protocol of 1 EVA per week. The associated risks are also within safe limits. However, it must be noted that we have not included radiation and possible accidents risks.

If those risks were added, and according to existing models, the risk associated to cardiovascular deconditiong should not exceed a 1-2% maximum risk. Furthermore, technological failures or solar events will certainly increase the total risk of the mission.

Conclusions

Numerical modelling has proven to be a valuable tool to predict possible risks of developing hazards in long-term mission scenarios. Our proposed electrical-like Model reproduces cardiovascular changes from previous modelling when returning to Earth, and has been validated from parabolic flight and comparison with former models of orthostatic intolerance.

Significant differences in heart rate output, mean arterial pressure and mean stroke volume appear in short-term scenarios. Also, long-term microgravity exposure simulations show a significant risk reduction, after aerobic exercise pattern applied, with gender differences, with women's more reduction than men's.

Microgravity exposure risks can be estimated for a variety of manned Moon and Mars scenarios, showing they are compatible with acceptable safety limits. EVAs are a significant added risk factor.

More studies are needed to fully understand the risks associated with the deconditioning of the cardiovascular system in long-term manned missions. These are the first steps of applying numerical multimodular models to the risk estimation of putting a manned space mission at risk.

References

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