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## **Numerical Simulation of Cardiovascular System Deconditioning in Different Microgravity Mission Scenarios, Risk Assessment and Countermeasures.**

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### **Abstract**

We report results from different intensive simulations aimed at evaluate the risks involved in a long-term exposure to hypo and hypergravity loads for a very extensive range of possible mission scenarios. The simulation allows us to introduce different levels of exposure to micro or hypergravity, analyse the consequences on relevant figures of cardiovascular deconditioning, such as heart rate, mean stroke volume or vascular resistance; and evaluate the relative risk of putting a mission into jeopardy due to microgravity deconditioning effects. Thermal stress, aerobic or anaerobic exercise are also simulated to take into account a realistic long-term space mission including, for example, ExtraVehicular Activities (EVA) or physical exercise as countermeasure. Gender differences have been found, with a significant difference in risk decrement for women compared with that in men, when aerobic exercise is simulated in long-term missions. The model is based on previous works from Melchier et al. or Heldt et al. who described in analytical terms the process of orthostatic intolerance due to gravity alterations being applied to a subject. We then incorporated these Runge-Kutta equations into a numerical model by using Matlab and Simulink software, to take into account the complex process of deconditioning of the cardiovascular system. Results from these models were validated in parabolic flight. The simulation is based on an electrical-like control system model in which output variables of the body performance (vascular resistance, blood volume etc) are found while step-by-step changes of gravity and thermal stress were applied. Different microgravity exposure scenarios, including Moon, Mars and other exploration missions are considered, and their associated risks are quantified. The more relevant results are provided, including the finding that the vascular resistance deconditioning appears to be alike in both microgravity and the reduced gravity at the level of the Moon. This deconditioning is not reversed by applying countermeasures; which raises concerns for successful manned Mars mission scenarios and others which include long-term microgravity exposure. Last results from these intensive numerical simulations of the deconditioning of the cardiovascular system show a variety of mission scenarios, with their risk assessment; which can be an optimal tool for planning long-term manned missions with hypo and hypergravity exposure.

**Keywords:** Numerical model, simulation, cardiovascular system, microgravity, orthostatic intolerance, parabolic flights.

### **1. 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.

### **2. Methodology of the simulation development**

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 [1]. 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.

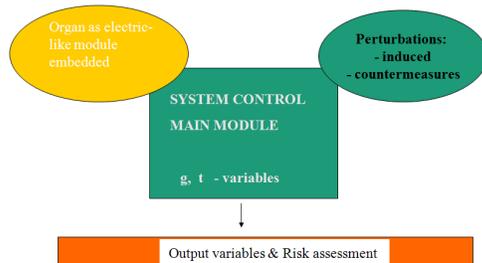


Fig. 1 Modular concept of NELME software analyser

Initial validation was performed by applying the Runge-Kutta equations model on orthostatic intolerance by Heldt [2] 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 ( $p < 0,05$ ).

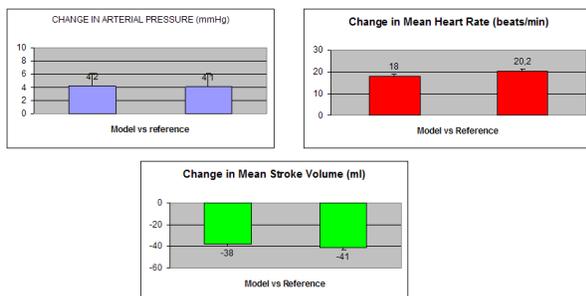


Fig. 2. Initial validation of the NELME model implementation.

Diaz-Artiles et al. [3] have implemented a computational model, compatible with our results, following Heldt's initial work [2], and studied short-

radius centrifugation combined with exercise as a potential countermeasure against spaceflight deconditioning.

### 3. Simulation of different scenarios

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 protocols. Then, risk reduction for the entire mission can be evaluated by using current standard procedures [4].

Furthermore, it is well known that the most stressful 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.

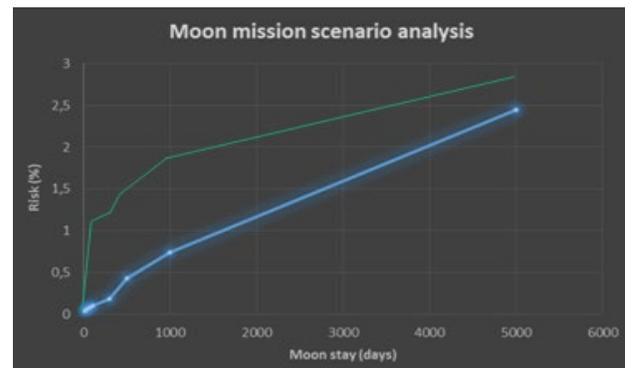


Fig. 3. Moon mission scenario analysis risk estimation (green: with 1/week EVA)

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).

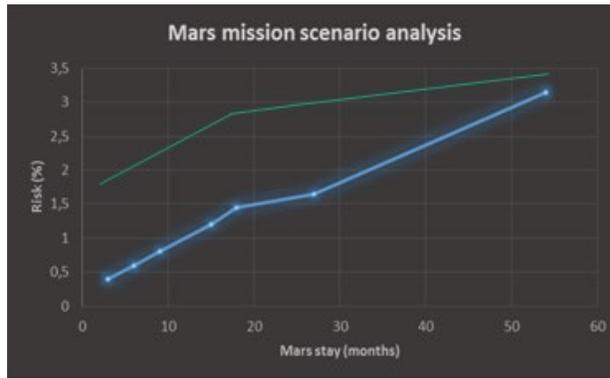


Fig. 4. Mars mission scenario analysis risk estimation (green: with EVAs)

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 deconditioning should not exceed a 1-2% maximum risk. Furthermore, technological failures or solar events will certainly increase the total risk of the mission.

#### 4. 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. Furthermore, 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.

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