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Lab-on-chip systems – new perspectives for microgravitional biomedical research in space

Agnieszka Krakos[1]
[1]Faculty of Electronics, Photonics and Microsystems, Wroclaw University of Science and Technology,
Wrocław 27 Wybrzeże Stanisława Wyspiańskiego st., Poland
agnieszka.krakos@pwr.edu.pl

Summary:

The investigation of the microgravity influence onto different biochemical and biomedical samples is the new research subject discussed in the literature widely. Especially interesting is the opportunity to use small scale, low-weight and fully autonomous lab-on-chip instrumentation to provide comprehensive research in space. According to the current NASA and ESA roadmaps, microfluidic and MEMS-based tools are more and more common, since apart from the ISS research conducted with an astronaut assistance, they can be successfully utilized for the autonomous, unmanned, and highly expertized astrobiological missions. In the paper, the overview of microfluidic technologies developed for space research will be discussed (nanosatellites missions, ISS investigation). Opportunities for microgravity simulation in Earth laboratories conditions with the use of lab-on-chip systems will also be described. The paper ends with a conclusion regarding the perspectives for microgravitional biomedical research.

Keywords: MEMS, microfluidics, microgravitional research, space science,

Background and Objective

Lab-on-Chip (LOC) technologies are pushing boundaries far beyond Earth's labs, with their applications in space research showing limitless potential. There's been a surge of interest in conducting research in the unique microgravity and radiation environments of space, showing atypical behavior of living specimens. Cutting-edge technologies are paving the way for a new generation of miniature instruments for what's called space biomedicine. The compact size of these devices offers significant advantages for space exploration, i.e. reduced launch costs and autonomous operation. This evolution in LOC applications is revolutionizing how we approach scientific research in the challenging conditions of space.

Biological nanosatellites

Though few biological nanosatellite projects have been launched, we've already seen that microgravity significantly impacts living organisms' development. NASA, for example, pioneered missions like GeneSat-1 (2006) and EcAMSat (2017), Fig. 1. These labs were equipped with Lab-on-Chip (LOC) structures, microfluidic components, and optical components, allowing for precise sample dosing, management, and analysis. The focus of both missions was to study *E. coli* bacteria. Researchers simultaneously assessed changes in their metabolism and proliferation using excited fluorescence techniques showing inhibited growth of E. coli colonies in a microgravity environment [1].

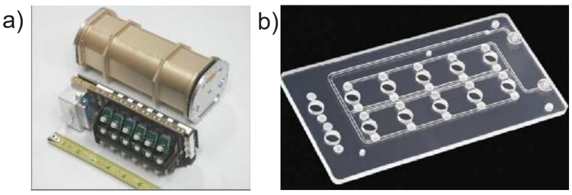

Fig. 1. Gene-Sat laboratory: a) payload, b) lab-chip.

Interesting mission strategies were provided with NASA's O/OREOS (2010) and LabSat (2022, Wrocław University of Science and Technology and SatRev, Poland). Both missions shared a key characteristic: they simultaneously ran two distinct experiments using a Lab-on-Chip (LOC) microfluidic laboratory. The O/OREOS mission used an LOC platform paired with an optical spectrometer to analyze changes in organic compounds like polycyclic aromatic hydrocarbons, amino acids, and quinones in space. Concurrently, O/OREOS investigated the "on-chip" development of *B. subtilis* and *H. chaoviatoris* bacteria. For both strains, researchers noted inhibited colony growth compared to how they grow on Earth [2].

The LabSat mission in turn aimed to study how microgravity affects the cultivation of *F. culmorum* fungi and *L. sativum* seeds. The microlaboratory integrated various microfluidic and optical components to enable direct examination of biological samples in orbit. Both fungal spores and cress seeds were loaded into lab-chips in a "dry" state. The cultivation process began once the nanosatellite reached its designated altitude and established radio communication. A vision system within the payload was programmed to capture images of the cultures multiple times daily. As a result of the mission, the images showing the germination of cress seed in Low Earth Orbit (LEO) could be captured.

Currently, no biological nanosatellite missions have experimented with more complex biosamples, such as human-derived ones. This limitation stems from the significant challenges in protecting these cells during rocket launches. Thus, stem and cancer cell research in microgravity primarily remains within projects conducted on the International Space Station (ISS).

ISS research

The International Space Station (ISS) offers numerous biomedical testing facilities, e.g. KUBIK, ABRS, EMCS, Bioculture System Facility (Fig. 2), and TangoLab-1. ISS is currently a home to several groundbreaking projects investigating how microgravity affects human cells. In a microgravity environment, cell cultures naturally form spheroids, mimicking how they appear in the human body. ESA's ESA-SPHEROIDS campaign and M4PM (Microgravity for Personalized Medicine) initiative are actively pursuing this research. So far, studies have revealed several significant changes in cancer cells exposed to microgravity. These include reduced proliferation, altered differentiation, changes in cell morphology, and the ability to form aggregations. These aggregations can minimize the impact of shear forces and stresses present in the extracorporeal environment, offering a unique perspective on cancer cell behavior.

Fig. 2. Bioculture System Facility.

NASA in collaboration with US institutions has also been driving the "Tissue Chips" project. This initiative leverages ISS facilities to study cell cultures, focusing on areas like cancer cells, drug resistance mechanisms (especially in kidney and heart tissue dysfunction), immunological changes, and musculoskeletal deconditioning. In 2023, the latest "Tissue Chips" campaign on the ISS, led by a consortium from Stanford University and Johns Hopkins Medicine, featured the Engineered Heart Tissues Chip (EHTs chip). This innovative chip allowed researchers to investigate the function of heart cells, model diseases, and determine the drug resistance of cardiomyocytes [3].

Microgravity simulation in Earth's labs

Beyond the ISS, academic communities are driving significant efforts in microgravity biomedical research. Given the limited capacity of the ISS and the complexities of constructing dedicated research nanosatellites, microgravity simulators are becoming the preferred initial tool for understanding phenomena caused by a quasi-microgravity environment. Instruments like the Random Position Machine (RPM), Rotating Wall Vessel (RWV), and Rotating Cell Culture System (RCCS) are widely used for studying biological samples. A more recent and interesting approach is diamagnetic levitation. Unlike the rotation-based simulators, diamagnetic levitation achieves limited graviperception through the use of magnetic force, offering a unique way to simulate microgravity conditions [4].

Conclusion

Microgravity biomedicine is a fascinating and rapidly evolving field that demands collaboration across numerous scientific disciplines. To create instruments capable of operating in the harsh environment of space, it's essential to leverage extreme technologies, including microelectronics, innovative materials, and intelligent, fully integrated autonomous computer systems. Further miniaturization of analytical devices, despite the inherent construction challenges and unique microscale phenomena, appears to be the most effective way to make microgravity biomedical research more accessible. Microfluidic lab-on-a-chip devices are increasingly being proposed for use in ISS projects, biological nanosatellite missions, and future research initiatives by NASA and ESA—even those extending beyond Low Earth Orbit (LEO).

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