Home

Space Life Science of China

MA Hong[1], REN Hao[1], LI Xiaoqiong[1], YANG Chunhua[1], CHEN Yu[1], WANG Rui[1], YING Zhang[1], WANG Changyong[2], ZHOU Jin[2], LI Hong[2], JIANG Xiaoxia[2], ZHANG Fengzhi[2], HAO Tong[2], ZHU Huimin[2], DONG Xiaohui[2] ZHENG Huiqiong[3], WANG Lihua[3], SUN Weining[3], TONG Guanghui[4], ZHENG Weibo[4], ZHANG Tao[4], LONG Mian[5], LIU Hong[6], ZHUANG Fengyuan[1], DENG Yulin[1]

1 (School of Life Science, Beijing Institute of Technology, Beijing 100081, China)
2 (Institute of Military Cognitive and Brain Sciences, Academy of Military Medical Sciences, Beijing 100850, China)
3 (Center for Excellence in Molecular Plant Sciences, Institute of Plant Physiology and Ecology, Chinese Academy of sciences, Shanghai, 200032, China)
4 (Shanghai Institute of Technical Physics, Chinese Academy of Sciences, Shanghai, 200083, China)
5 (National Microgravity Laboratory, Institute of Mechanics, Chinese Academy of Sciences)
6 (School of Biological Science and Medical Engineering, Beihang University, Beijing 100191, China)

Abstract

With the human space exploration activities, space life science is an emerging interdiscipline, which covers a wide range of researches. Based on our country′s manned space station and recoverable satellite science experimental platform, the development of space life science research is very important to acquire new knowledge or new technological innovation, to give further services to the human space exploration activities, to improve the national economic and social development. Both ground based and flight applied studies were continuously performed in the previous 2 years. Here, we review and summarize the researches on space life sciences contributed by Chinese scientists.

Key words

Space life sciences, Space payload, Ground based study, Flight applied study, China

National Report 2016–2018

E-mail: deng@bit.edu.cn

1. Payloads in Space Life Science

It is worth noting that, the conducting of space life sciences and space medicine research cannot be separated from scientific instruments and equipment. To some extent, experimental instruments (payloads) determine the research capabilities in space. However, due to the particularity of the space science instruments (payloads), it is difficult to rely on imports from abroad, and thus efforts should be concentrate on independent innovation and research of the space science instruments (payloads). The payload operation is currently recognized as the most effective control platform for the science research in space station.

The goal of China’s manned space station is to build a national space laboratory. In response to the future demand of manned space stations, the Ministry of Science and Technology approved a special project for the development of major scientific instruments and equipment in October 2012 – “Space multi-indicator biological analysis instrument development and application”. The project manager is Professor Yulin Deng from Beijing Institute of Technology, and the manager of industrialization is Professor Yutu Zhang from Shandong Institute of Aerospace Electronic Technology. This project aims to develop a multi-indicator bio-analytical integrated instrument platform involving biological cultivation, on-orbit online analysis, and data processing, providing important scientific payloads for manned spaceflights, deep space exploration and other aerospace projects to meet the needs of space life sciences research. Since the implementation of the project, key technologies such as space cell culture technology, space protein and nucleic acid microfluidic chip analysis technology, space miniaturization mass spectrometry technology, development of multi-task multi-objective material flow and information flow control technology have been successfully tackled; space multi-indicators bio-analyzer has been completed; and three space flights have been performed, having extensive influence at home and abroad. Simultaneously, a large number of research results in space life sciences, aerospace medicine, fundamental researches and civilian applications have been obtained.

Given that the aerospace or the manned space experiment platform's features – "mainly automatic operation, supplemented by manual operation", the instrument supports two working modes: in-place operation experiment and remote control experiment. The remote-control software can realize the resource allocation, control of the whole instrument through the central control information system, real-time display and control of the working status, as well as analyze and store the received experimental data. The central control information system supports the flat end-to-end push of the instrument′s digital interface, enabling users to operate easily at any location on the space station or on the ground control center.

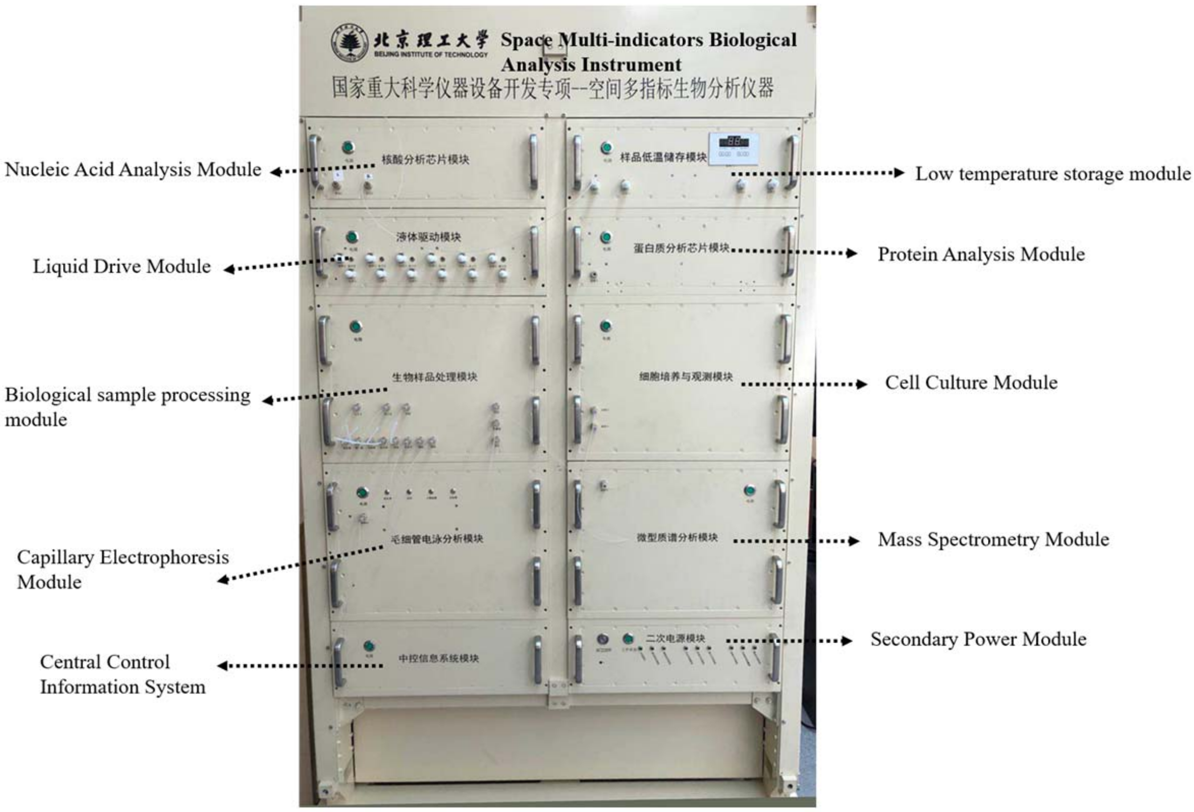


Fig. 1 Appearance of space multi-indicators biological analysis instrument

2. Space Cell and Microbial Culture Experimental Payload in Long March 7

During the implementation of the mission, one space flights have been fulfilled carrying some of the functional modules in the form of payloads, obtaining important on-orbit experimental data and having a positive and widespread impact.

In June 2016, the "Space Cell and Microbial Culture Experimental Payload" first flew into space with the "Long March 7", and came back with "Multi-purpose Space Return Capsule", completing the space carriage experiment, in order to meet the special needs for microbiological safety and control in the construction of China’s manned space station, This space carriage experiment focuses on the effects of proliferation and variation of microorganisms in space environment on the long-term operational safety of space platforms. Corrosive microorganisms in the space station and space station assembly plant in China were selected to be sent into space for a short period of time.

The physiological, biochemical and molecular indicators of the returned samples show that the space environment will, to a certain extent, promote the variation and evolution of microorganisms, and accelerate their corrosion process on space platforms. The results have been applied to assist the guidance of relevant departments of China’s manned space system to establish prevention and control plans for key microorganisms of the space microbiology, which reasonably optimizes the ground assembly environment of the space station and ensures the on-orbit biosafety of the platform.

3. Space Payload in Tianzhou-1

3.1 Investigations of Microgravity Effect on the Biological Characteristics of Cells

Humanity has a strong curiosity and a practical need to explore the space, exposure to extraterrestrial microgravity is inevitable during the process. Aviation medical research results have shown that long-term flight in space environment affects almost all the aspects of human physiology. Microgravity can cause wide and serious consequences such as arrhythmia, cardiac atrophy, osteoporosis and muscle atrophy, which all threatens astronauts′ bodies.

The influence of spatial microgravity on the cells of human body has become a hot topic in biological research. The effects of simulated microgravity on a variety of cells/tissues can be studied using a NASA proved RCCS rotating bioreactor system. By the RCCS system, Embryonic Stem Cells (ESCs) can efficiently form embryoid bodies. Both the number and quality of those embryoid bodies are better than the ordinarily cultured, with their stem cell characteristics maintained. ESCs are reengineered into the rhythmic contractile myocardial tissue for the first time. Islet tissue can also be engineered under RCCS system, and it maintains good function of insulin synthesis and secretion in diabetic rats after transplantation under renal capsule for 3 months. In addition, human blood lymphocytes or mononuclear cells can be long-term cultured in RCCS system in vitro, and the effects of simulated microgravity on the immune function are investigated. Researchers further screened out three drugs for increasing the immunity under microgravity---Letinous edodes Nucleosides, Polysaccharide and Cordyceps Polysaccharide.

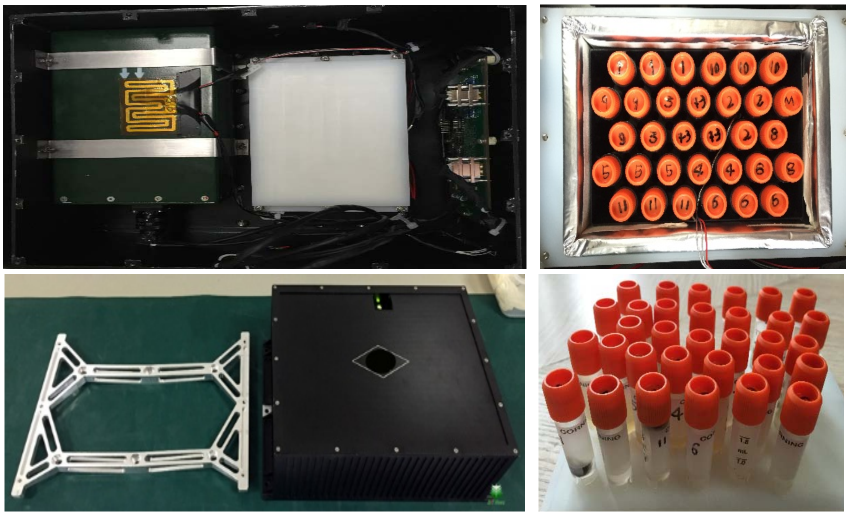
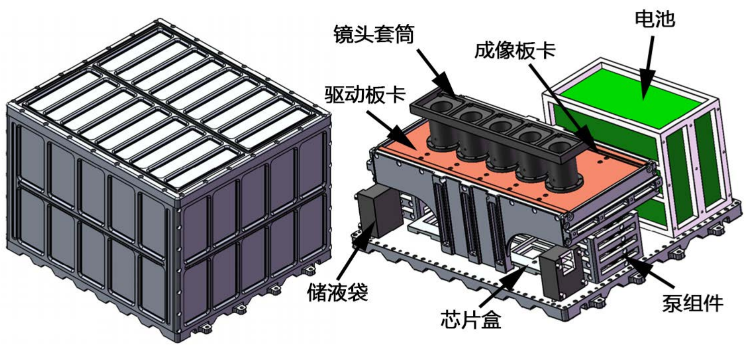


Fig. 2 Outer view of space cell and microbial culture payload

The discovery of induced Pluripotent Stem Cells (iPSCs) is an important landscape in stem cell research. iPSCs have pluripotent differentiation potential, but overcoming obstacles of ethical issue and a shortage of supply. Taking opportunity of the mission of Tian Zhou spacecraft (TZ-1), Prof. Wang Changyong from Academy of Military Medical Sciences used iPSCs to investigate the real space microgravity influences on the regeneration and myocardiac differentiation. The self-designed and developed Space Bioreactor System of TZ-1 firstly realized the spatial dynamic cultivation of cells and the microscopic observation during the whole experiment process as well. After several shock experiments, biological reactor matching tests, murine OCT4-eGFP-iPSCs, αMHC-eGFP-iPSCs and their embryoid bodies were successfully integrated into the bioreactor of the TZ-1 spacecraft, which launched on April 20th, 2016, flying about 380 kilometers above the earth. The cell image data transmitted to the ground automatically every day, and parameters or modes could also be adjusted by uploading commands from the ground. The ground control experiment was carried under identical conditions to the spaceflight except for exposure to 1*g* ground gravity of earth. The results here evidenced for the first time that iPSCs can proliferate and myocardiac differentiation in the space under real microgravity circumstance. The proliferation ability of iPSCs was significantly enhanced, and the two iPSCs lines mutually confirmed that the microgravity promotes cardiomyocyte differentiation of iPSCs. Taken together, these results augmented the current knowledge about the microgravity effect on the biological characteristics of cells. The strategies can also be used in tissue engineering, drug screening, and disease prediction for boosting the health of humanity in the future.

3.2 Space Microfluidic Chip Bio-cultivation and Analytical payload

In April 2017, “Space Microfluidic Chip Bio-cultivation and Analytical payload” was launched with the launch of China’s first cargo spaceship “Tianzhou-1” at Wenchang Satellite Launch Center followed by a two-week on-orbit science experiment mission. This highly integrated, automated experimental device supports on-orbit co-culture of nerve cells and immune cells, in-orbit biochemical analysis, and on-orbit processing and transmission of experimental data. The related technologies have reached the international leading position in life sciences. During the three years’ implementation of the project, a number of key technologies have been successfully broken through and met the stringent quality management requirements of the aerospace system. Finally, all experimental tasks were successfully completed in this flight experiment.



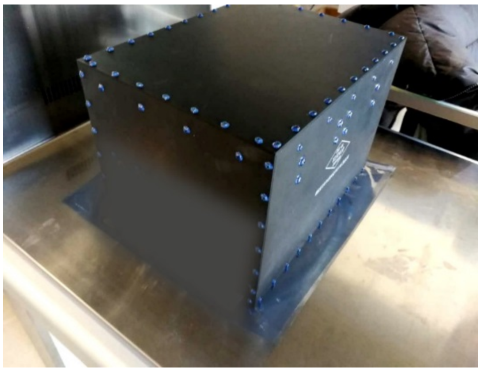


Fig. 3 Space microfluidic chip bio-cultivation and analytical payload

4. Photoperiod-controlling Clowering and Seed to Seed Growth on Board the Chinese Spacelab TG-2 and the Chinese Recoverable Satellite SJ-10

The most pronounced alteration in plant development is the transition from vegetative to floral growth, which is regulated by environmental and internal signals. Gravity is one of the most important environmental factors and has always been present during evolution, but if altered gravity influences the flowering time is still unknown. In the last two years, we have studied the microgravity effects on photoperiod-controlling flowering and seed to seed growth of *Arabidopsis thaliana* and rice on board the Chinese recoverable satellite Shijian (SJ-10) and the Chinese spacelab Tiangong (TG-2), respectively. A Plant Growth Box (PGB) is constructed specially for the higher plant growth and development experiments under a long-day (16h light/8h dark) and a short-day (8h light/16 h dark) condition on board TG-2 and SJ-10 (Fig. 1). GFP Florence detector and photo imager as well as life support such as water and light systems are also included in PGB system.

In Arabidopsis, flowering is promoted by increasing day length and delay in short day condition. In contrast, rice is a short-day plant, flowering more rapidly in short-day-length conditions than in long days. This photoperiod response is based on the plants, which are grown in a 1*g* ground environment, but whether and how gravity influence plant flowering was not reported before. Our experiments are the first time to study the effects of microgravity photoperiod controlling flowering in space. The experiment onboard the SJ-10 satellite was carried out for relative short-term in space, which was about 13 days in space during April 6-18, 2016, while the TG-2 experiment was a long-term study in space, which was more than 850 days during September 23, 2016 to January 30, 2018. Thus, we can study the different effects of short- and long-term microgravity on the plant seed to seed growth by comparing the results of these two different space experiments.

Conditions

Plant material: *Arabidopsis thaliana* and rice seeds;

Temperature：17°C~28°C；

Humidity：60%~100%；

Light intensity：120~200 μmol/m^2·s；

Photoperiod: 16 h light/8 h dark (long-day), 8h light/16 h dark (short-day).

Hardware

The Plant Growth Box (PGB) is configured as two separate units, the Orbit Growth Unit (OGU) and the Recoverable Growth Unit (RGU) (Fig.4). The OGU, whose envelop dimensions are 33×23×30 cm^3 (L×W×H), will be used for the experiments only in orbit and will not return. This OGU has self-contained sealed atmospheres and four Culture Chambers (CCs). Each CC consists of a polycarbonate base and a transparent polycarbonate lid that fit together over a silicone rubber gasket. The lip has two cut-outs covered by a gas-permeable membrane. Lighting for plant growth is provided by LED lamps, 16 h on/8 h off period (long-day) and 8 h on/16 h off period (short-day), 120 μmol m^{-2} s^{-1}/200 μmol m^{-2} s^{-1} photosynthetically active radiation for Arabidopsis and rice, respectively. Temperature is 17°C~23°C. Images are recorded by two automatic, preprogrammed cameras and one GFP imager. The water system is included in the OGU, which can pump nutrient medium from reservoirs into CCs. The RGU, whose envelop dimensions are 7×7×31.2 cm^3 (L×W×H), is used for growth of Arabidopsis from seeds to seeds and return to Earth. The life support for RGU is similar to that in OGU. All manipulations involved in the experiment are automated or carried out by remote control.

In the SJ-10 experiment, we used the advantages of Heat Shock (HS)-inducible gene switch and developed transgenic Arabidopsis containing the *HSP17.4* gene promoter linked to the Green Fluorescent Protein (GFP) reporter gene (*HSPpro*::*GFP*) and the *FT* gene

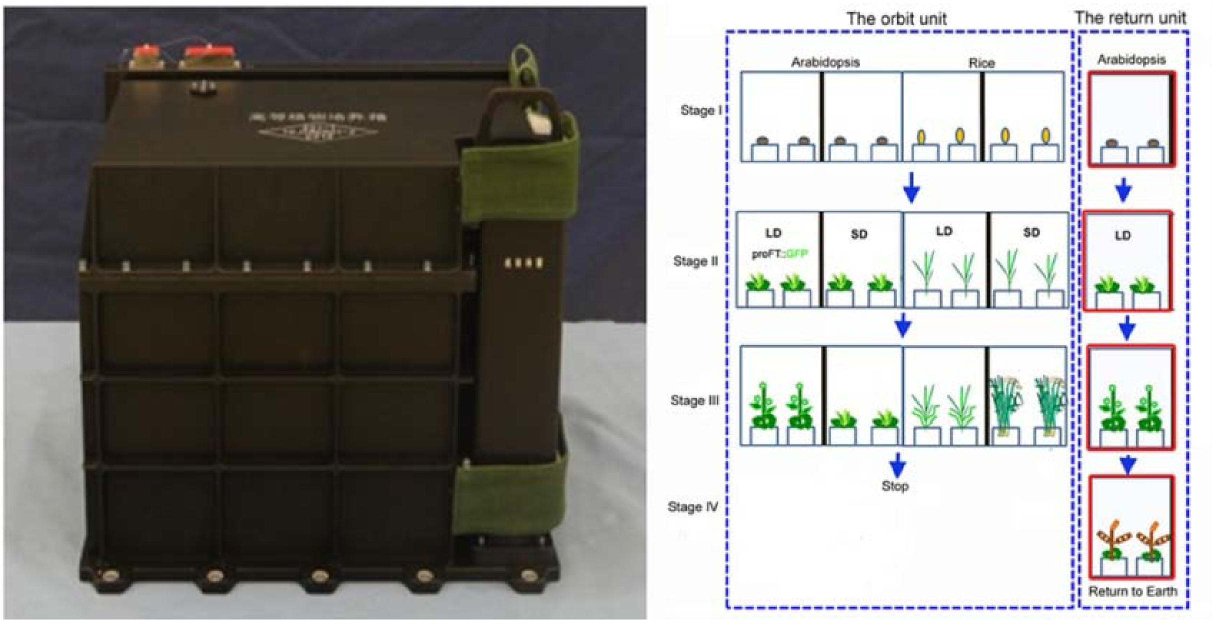


Fig. 4 Plant Growth Box (left plane) and schematic schedule of space experiments in PGB (right plane)

(*HSPpro*::*FT*), respectively. The expression of *HSPpro*::*GFP* and *HSPpro*::*FT* in Arabidopsis leaves at 37°C under short-day conditions, were monitor by a plant GFP imager. In the same time, time-lapse images also documented the effect of microgravity on the flowering induction of Arabidopsis and rice plants under a long-day and a short-day condition, respectively. 37°C heating for 30 min induced strong expression of *GFP* and *FT* in the leaves of Arabidopsis plants in microgravity but flowering time apparently delayed. For the first time, the importance of gravity in expression of FT gene and its induction flowering in microgravity was unequivocally demonstrated. The network of transcriptional regulation of flowering gene expression was also analyzed.

Onboard TG-2, we performed an experiment with the objective to grow Arabidopsis thaliana and rice plants from seed-to-seed under different photoperiod conditions. Dry Arabidopsis and rice seeds were planted in the culture container of the PGB. The seeds of Arabidopsis were successfully germinated, grew and completed a full life cycle in microgravity under the long-day condition and the short-day condition transferred to the long-day condition before flowering. This experiment demonstrated that the flowering of both Arabidopsis and rice plants was significantly delayed in microgravity condition. To delineate the transcriptional response mechanisms, we also carried out whole-genome microarray analysis of Arabidopsis leaves of plants which grown on board the TG-2 and its ground control conditions, respectively. We identified a novel set of microgravity response genes, recognized mainly by quantitative differences. These included a transcriptome signature of more pronounced proline transport in developing leaves. This study provides developmental stage specific molecular resolution of different age leaves and demonstrates that a new molecular plasticity in Arabidopsis leaves to adaptation to microgravity by adjusted genome status during development in space.

5. Space Molecular Evolution Payload in International Space Station

On June 2017, "Space Molecular Evolution Payload" entered the International Space Station's Dragon cargo spacecraft and were successfully launched for a one-month on-orbit experiment. As the first time that China entered the "International Space Station" to carry out scientific experiments, microfluidic chip technology was utilized to realize the in-situ amplification of multiple immune gene to study gene mutation mechanisms under space radiation and microgravity. During the development process, research group successfully broke through the molecular biology techniques of variable temperature PCR amplification in space conditions, the development of space multi-task microfluidic amplification chips, and the maintenance of enzyme effectiveness for long-term.

This "ice breaker" space carriage was the first cooperation between China and the United States in the space field over the past 30 years. It has opened up a new way for Chinese-American space cooperation through the commercial cooperation. In order to ensure the smooth implementation of the payload development, launch, and recycling, the teams of the two sides made frequent trips to China and the United States and set up laboratories at the Kennedy Space Center. The experiments were successfully completed, and received high praise from US partners and scientists. Domestic and foreign media have extensive reported, resulting in a wide range of international and domestic influence.

6. A Novel Space Cell Culture System (SCCS) in SJ-10 Satellite

Research in microgravity is indispensable to disclose the impact of gravity on biological processes and organisms. Ground-based simulators of microgravity are valuable tools for preparing spaceflight experiments. The various microgravity simulators that are frequently used by gravitational biologists are based on different physical principles. The effects of ground-based microgravity on biological specimens are investigated by using simulators. In this section, current heterogeneous researches are discussed critically, and a summary is given for comprehensive understanding of the influence.

This work aims at understanding how gravity-vector regulates the mechanical stability of mammalian cells. Experimentally, the remodeling of an MC3T3-E1 cell placed in upward-(U), downward-(D), or edge on-(E) orientated substrate is quantified. Nucleus longitudinal translocation presents a high value in D at 24h or in E at 72 h, consistent with orientation-dependent distribution of perinuclear actin stress fibers and vimentin cords.

Fig. 5 Space molecular evolution payload and schematic schedule of space experiments in International Space Station

Redistributions of total Focal Adhesion Complex (FAC) area and fractionized super mature adhesion number coordinate this dependence at short duration. Moreover, this orientation-dependent remodeling is associated with nucleus flattering and lamin A/C phosphorylation. Actin depolymerization or Rho-associated protein kinase signaling inhibition abolishes the orientation dependence of nucleus translocation, whereas tubulin polymerization inhibition or vimentin disruption reserves the dependence. Theoretically, a biomechanical model is thus proposed to integrate the mechanosensing of nucleus translocation with cytoskeletal remodeling and FAC reorganization induced by the gravity vector. Under gravity, dense nucleus tends to translocate and exert additional compressive or stretching force on the cytoskeleton. Consequently, the changes in the tension force acting on talin by microfilament alter the size of FACs. Theoretical predictions from the model are in agreement with those from experiments.

In 2016 and 2017, Chinese scientists group was focused on elucidating the mechano-biological coupling mechanisms of mammalian cells under microgravity and developing the novel techniques in cell biomechanics and bioengineering. Prof. Long Mian and his group focused on cell growth and differentiation associated with controllable mass transportation under microgravity – an experiment on SJ-10 recoverable satellite. This study attempts to develop a novel Space Cell Culture System (SCCS), mainly consisting of precisely controlled flow chamber and gas exchange unit, to investigate the responses of endothelial cells and Mesenchymal Stem Cells (MSCs) associated with mass transportation under microgravity. The primary goal is to isolate the direct responses of the cells from those indirect responses via the varied mass transport conditions induced by gravity changes. The specific aims are to collect the data on the metabolism, proliferation, apoptosis, differentiation, and cytoskeletal remodeling of endothelial cells and mesenchymal stem cells under well-defined mass transportation in space. Comparative analyses of the data between space sample (12-day mission in SJ-10 satellite in April, 2016) and ground-based control indicate that flow-induced mass transport patterns could alter cellular metabolism. Under microgravity, the endothelial cells and MSCs respond differentially in initiating cytoskeletal remodeling, dysregulating signaling pathways relevant to cell adhesion, or directing hepatic differentiation. These results provide an insight into the mechanosensing and mechanotransduction of mammalian cells under space microgravity.

Meanwhile, they also focused on the effects of gravitational stress on the efficiency of innate immune responses via characterization of neutrophil migration performance–an experiment on parabolic flight. This study proposes to characterize how immune cell function is affected by altered gravity produced by parabolic flight (30 th DLR parabolic flight, a 4-day mission in September, 2017) using an integrated biomechanical and biomedical approach with forced fluid flow and on-line cell imaging, allowing to elucidate the rolling and adhering features of Jurkat cells and Peripheral Blood Mononuclear Cells (PBMC) on flow chamber substrate coated with different adhesion molecules. In the presence or absence of IL-8 stimulation, cell adhesion dynamics, adhesion molecule expression, and cytoskeletal remodeling of on-line fixed cells in different phases of altered gravity are analyzed post-flight. Data from these tests complement the picture of the effects of gravitational stress on the efficiency of innate immune responses.

7. Research Progress on Bioregenerative Life Support Systems

Bioregenerative Life Support Systems (BLSS) are artificial ecosystems consisting of many complex symbiotic relationships among higher plants, animals and microorganisms. As the most advanced life support technology, BLSS can provide a habitation environment similar to the Earth's biosphere for extended-duration missions with multiple crewmembers in deep space. Almost all requirements for human life support can be produced within BLSS, including fresh air, clean water and nutritionally valuable food. Progress in achieving manned space flight in China is moving forward rapidly, which is also driving the development of BLSS technology.

A series of studies to advance BLSS have been conducted by Professor Hong Liu's team from Beihang University. Starting from a theoretical basis, an integrated BLSS design methodology was created, and conceptual configurations of the Moon and Mars bases were established to identify the basic structural forms and the involved biological components of BLSS. Additionally, a stoichiometric model was built to describe the material balance among the components to clarify the mass flow property of BLSS. Based on the above fundamental work, a series of studies were carried out on the key biological units, including plant cultivation, animal breeding, and waste treatment.

The crop candidates were selected according to Chinese sitology criteria and dietary habits, which would meet the special requirements of the BLSS as well. Porous tube-culture technologies were then successfully established for these crops, and the effects of environmental factors, such as CO_2 concentration and light source on crop growth were subsequently assessed. The experimental results demonstrated that the optimal CO_2 concentration for the cultivation of wheat, soybean and leaf vegetables was 1000–3000 $\mu mol \cdot mol^{-1}$. In addition, a red-white LED was more conducive to the growth of wheat and quality improvement of leaf vegetables compared to a red-blue LED, which indicated that the former was a more appropriate light source choice for plant cultivation.

Two candidate insects, silkworm and yellow mealworm, were proposed as a source of animal protein for astronauts in the BLSS. These insects have higher nutritional value than previously proposed animal candidates (fish, pig, *etc*.), and are easier to rear and manage in a space station. Most importantly, these insects could be fed on plant waste (*e.g*., straw, bran, vegetable roots and old leaves) in the BLSS, which would improve the closure and stability of the system. Theoretical modeling results showed that the closure coefficient of BLSS containing yellow mealworm and silkworm could reach 99.53% and 99.40%, respectively, which were both higher than that of a BLSS without an animal-rearing unit (98.68%).

In terms of solid waste treatment, a Soil-Like Substrate (SLS) technology was established to process the inedible parts of plant and human feces utilizing microbes and earthworms. A series of SLS preparation devices were constructed with optimized parameters to shorten the preparation period, and an efficient and controllable solid waste bio-convertor was built based on the aerobic microbial fermentation to treat the mixture of the inedible plant biomass and human wastes. Microbial fuel cell technology was also studied to treat feces and generate electricity simultaneously. On the other hand, photobioreactors cultivating microalgae and a urine hydrolysis method combining immobilized urease catalysis and reduced pressure distillation have been constructed and investigated for urine purification and recovery to increase the closure of BLSS.

Besides the experimental tests, the above technologies were subjected to computational studies using control theory in combination with computer simulations to ensure the effective integration of each component and the stable operation of the entire system. A mathematical and simulation model describing the long-term and continuous preparation process of SLS was formulated. Moreover, a valid kinetic model was developed to fully describe the dynamic characteristics of O_2 concentration in the photobioreactor, and optimized for the regulation of the gaseous components in BLSS during emergency situations, a feature that would be helpful for keeping the system operating robustly with increased safety and reliability. The highly nonlinear characteristics of the photosynthesis rate of higher plants were also effectively studied by means of mixed-effects models, which were sufficient to describe the photosynthetic response of lettuce to the CO_2 concentration.

After the in-depth study of each biological component of the BLSS, Prof. Hong Liu's team designed and constructed an integrative ground-based BLSS experimental facility, referred to as Lunar Palace 1, containing human, plant, insect, and microbial components. Compared to the closed system tests in Russia, USA, and Japan, Lunar Palace 1 was evaluated to be the most complex system in terms of its biological components, integrating plant cultivation, animal protein production, and microbial bioconversion of wastes. A 105-day closed experiment with three crewmembers was conducted in Lunar Palace 1 (Stage I) in 2014. During this experiment, 100% of oxygen and water, and 55% of the food requirements for three crewmembers were regenerated, and 97% of system closure coefficient was achieved, surpassing the duration and overall system closure of any prior and related tests with bioregenerative systems. Subsequently, a 365-day bioregenerative life support experiment, 'Lunar Palace 365', was carried out in the upgraded and completed Lunar Palace-1 from May, 2017 to May, 2018, aiming to achieve a higher degree of food supply and system closure than the previous research. Furthermore, the stability of the artificial closed ecosystem with four biological loops, 'human-plant-animal-microorganisms', were tested in various circumstances such as the crew shifts and the loss of power, and the psychological changes of crew members with different combinations during the long-term BLSS experiment and the interaction with gut microbiome, the developmental succession of environmental microorganisms, the impact of light environment and plant environment on human beings were also studied.

8. Conclusion

With the development of the national economy, a series of National Science and Technology Major Projects have been successively approved: China Manned Space Station Project, Lunar Exploration Project, Deep Space Exploration mission, etc., providing an unprecedented opportunity for space life sciences and space medicine researches. The researches on space life sciences will hopefully contribute to understanding the origin of life on the earth and the mechanisms of evolution, and to developing the knowledge and methods to enable humans to endure long-term stays in space with protection from the spaceflight effects.

References

[1] Li, R; Zhang, XJ; Lv, XF; Geng, LN; Li, YR; Qin, KW; Deng, YL. Microvalve controlled multi-functional microfluidic chip for divisional cell co-culture. Analytical Biochemistry 539: 48-53, 2017.

[2] Zhang, CX; Lv, XF; Yasmeen, S; Qing, H; Deng, YL. Integrated microfluidic chip with nanobiosensor for rapid and label-free detection of a specific gene. Analytical Methods 9(24): 3619-3625, 2017

[3] Wang, Y; Javed, I; Liu, YH; Lu, S; Peng, G; Zhang, YQ; Qing, H; Deng, YL. Effect of Prolonged Simulated Microgravity on Metabolic Proteins in Rat Hippocampus: Steps Toward Safe Space Travel. Journal of Proteome Research 15(1): 29-37, 2016.

[4] Qin, KW; Lv, XF; Xing, QR; Li, R; Deng, YL. A BSA coated NOA81 PCR chip for gene amplification. Analytical Methods 8(12): 2584-2591, 2016.

[5] Yu, SY; Xu, JD; Huang, KJ; Chen, J; Duan, JY; Xu, YQ; Qing, H; Geng, LN; Deng, YL A Novel method to predict protein aggregation by two -dimensional native protein microfluidic chip electrophoresis. Analytical Methods 8: 8306-8313, 2016.

[6] Li, R; Lv, XF; Xu, JD; Xu, YQ; Wang, JS; Qin, KW; Zhang, XJ; Zhou, D; Deng, YL. A Rapidly Fabricated Microfluidic Chip for

Cell Culture. Journal of Chromatographic Science 54(4): 523-530, 2016.

[7] Li, R; Lv, XF; Zhang, XJ; Saeed, O; Deng, YL. Microfluidics for cell-cell interactions: A review. Frontiers of Chemical Science and Engineering 10(1): 90-98, 2016.

[8] Zhou L, Zhang C, Zhang F, Lü S, Sun S, Lü D, Long M Theoretical modeling of mechanical homeostasis of a mammalian cell under gravity-directed vector. Biomech Model Mechanobiol. 17(1): 191-203, 2018.

[9] Zhang C, Zhou L, Zhang F, Lü D, Li N, Zheng L, Xu Y, Li Z, Sun S, Long M. Mechanical remodeling of normally sized mammalian cells under a gravity vector. FASEB J. 31(2): 802-813, 2017.

[10] Wang M, Fu Y, Liu H. Nutritional quality and ions uptake to PTNDS in soybeans. Food Chem. 1;192: 750-759, 2016.

[11] Li L, Xie B, Dong C, Hu D, Wang M, Liu G, Liu H. Rearing Tenebrio molitor L. (Coleptera: Tenebrionidae) in the “Lunar Palace 1” during a 105-day multi-crew closed integrative BLSS experiment. Life Sci Space Res (Amst). 7: 9-14, 2015.

[12] Qin Y, Fu Y, Dong C, Jia N, Liu H. Shifts of microbial communities of wheat (Triticum aestivum L.) cultivation in a closed artificial ecosystem. Appl Microbiol Biotechnol. 100(9): 4085-95, 2016.

[13] Fu Y, Li L, Xie B, Dong C, Wang M, Jia B, Shao L, Dong Y, Deng S, Liu H, Liu G, Liu B, Hu D, Liu H. How to Establish a Bioregenerative Life Support System for Long-Term Crewed Missions to the Moon or Mars. Astrobiology. 16(12): 925-936, 2016.

[14] Dong C, Fu Y, Xie B, Wang M, Liu H. Element Cycling and Energy Flux Responses in Ecosystem Simulations Conducted at the Chinese Lunar Palace-1. Astrobiology. 17(1): 78-86, 2017.

[15] Chen Y, Zhang J, Cen JL, Sun FY, Chen B; Deng YL, Ma H. Cell culture of nerve cell and immune cell in CO_2-free environment based on microfludic chip. Transaction of Beijing Institute of Technology 37(suppl.1): 1-6, 2017.