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Original Article

The Potential of Space in Advancing Cancer Treatment: A Review

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ABSTRACT
The treatment of cancer has undergone revolutionary changes throughout the years, moving from traditional surgery, chemotherapy, and radiation therapy to advances in precision medicine and immunotherapy. Concurrently, space-based research has become a cutting-edge area of biomedical inquiry. Investigations of cellular activity, tumor progression, medication response, and immunological regulation are made possible by the special circumstances of microgravity, cosmic radiation, and changed fluid dynamics in space, which are not possible on Earth. This paper discusses the development of three-dimensional tumor models, the effects of microgravity on cancer cell biology, and the implications for immunotherapy and medication development. It summarizes recent results from space studies. Additionally, the review looks at how space radiation studies have advanced radiation therapy, how artificial intelligence and nanotechnology can optimize experimental protocols, and what ethical and regulatory frameworks are required to translate these findings into clinical practice. by the integration of many studies [1–8, 15, 19, 23, 28, 31, 34, 37, 42, 45, 51, 55, 59, 63, 67, 71, 75, 78], the potential of space research to transform oncology and enhance patient outcomes is highlighted in this review.
Keywords: Cancer Treatment, surgery, chemotherapy, and radiation therapy, artificial intelligence and nanotechnology

INTRODUCTION

Although there have been significant advancements in diagnostic and treatment techniques, cancer remains one of the major causes of death globally. [1, 2, 9]. Drug resistance, systemic toxicity, and tumor recurrence are some of the problems that usually restrict the effectiveness of conventional treatments, which include surgery, chemotherapy, and radiotherapy [3, 10]. Targeted treatments and immunotherapy have shown encouraging outcomes since their introduction. [4, 11, 12], yet challenges remain [5, 13, 14]. Space-based research has recently offered an unorthodox platform for studying cancer biology in environments of cosmic radiation and microgravity. [6, 7, 8]. Research on the International Space Station (ISS) and other orbiting platforms has demonstrated that microgravity causes distinct biological reactions, such as changes in gene expression, cell signaling pathways, and cell shape. [15, 16, 17]. In addition, compared to conventional two-dimensional (2D) cultures, the development of three-dimensional (3D) tumor models in space has produced more accurate depictions of tumor microenvironments. [18, 19, 20].This review explores the ways in which space research advances our knowledge of cancer, highlighting the following important topics:

• Microgravity's effects on gene expression, apoptosis, and cancer cell proliferation [21–23]
• The advancement and benefits of three-dimensional tumor models in microgravity [24–26].
• Developments in drug research, including as protein crystallization and drug absorption investigations, made possible by space-based experiments [27–29].
• The impact of microgravity on immunotherapeutic approaches and immune cell function [30–33].
• New findings in space radiation research and how they relate to enhancing radiotherapy methods [34–37].
• The use of computer modeling and nanotechnology in space medicine [38–41].

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• The difficulties in integrating space-derived insights into clinical oncology, including ethical, regulatory, and research issues [42–45, 48, 50].

By reviewing these interdisciplinary contributions [46, 47, 49, 52–54, 56–58, 60, 61, 62, 64–66, 68–70, 72–74, 76–80], The potential of space-based cancer research to influence and revolutionize terrestrial oncology is thoroughly discussed here.

2. Microgravity and Its Impact on Cancer Cells

2.1 Cellular Behavior in Microgravity

The substantial impacts of microgravity on cellular activity include changes in proliferation, differentiation, and death [15, 17, 21]. Research on the International Space Station has shown that cancer cells exposed to microgravity develop 3D spheroids rather than the typical 2D monolayers found on Earth [22, 24, 25]. These spheroids more precisely mimic the architecture of tumors in vivo, meaning they offer valuable information about drug penetration, oxygen diffusion, and nutrient gradients [26, 27, 28]. The effects of sedimentation are lessened when the fluid dynamics under microgravity affect the mechanical forces acting on cells [29, 30]. This alteration affects the interactions between cells and the extracellular matrix, which are necessary to comprehend the possibility of metastasis [31, 32, 33]. Additionally, it has been demonstrated that microgravity changes the cytoskeletal architecture, which is crucial for invasion and cell movement [34, 35].

2.2 Molecular Pathways and Gene Expression

According to gene expression investigations, microgravity significantly alters the pathways that control cell survival, apoptosis, and stress response [36, 37, 38]. A number of studies, for example, have documented changes in the expression of genes related to cytoskeletal proteins, adhesion molecules (such as cadherins and integrins), and the extracellular matrix [39, 40, 41]. The accelerated development of tumor spheroids and changed metastatic behavior seen in microgravity circumstances could be explained by these molecular alterations [42, 43, 44]. Furthermore, it appears that microgravity modifies oxidative stress responses, which could change the ratio of apoptosis to cell growth [45, 46, 47]. Because many chemotherapeutic drugs produce reactive oxygen species (ROS), such alterations in redox equilibrium may affect how cancer cells react to chemotherapy [48, 49, 50]. Additionally, it has been demonstrated that microgravity alters the expression of multidrug resistance (MDR) proteins, including P-glycoprotein [51, 52].

2.3 Implications for Drug Resistance

One of the biggest obstacles to cancer treatment is the emergence of medication resistance [53, 54, 55]. Microgravity research has shown that cancer cells may change the expression of important mediators of drug resistance, providing novel ways to combat resistance mechanisms [56,57]. Researchers aim to discover new molecular targets that can make cancers more sensitive to traditional treatments by examining these cellular alterations in space [58,59,60]. Clinical results could be improved by designing next-generation medications that are less prone to resistance as a result of these discoveries [61, 62, 63].

3. Space-Generated Insights into Tumor Growth

3.1 Three-Dimensional Tumor Models

The development of three-dimensional tumor spheroids in microgravity has significantly advanced the research of cancer [24, 64, 65]. Unlike typical 2D cell cultures, these 3D models reproduce the complex architecture of tumors, including gradients of oxygen, nutrients, and metabolites [66, 67, 68]. This enables more accurate studies of the tumor microenvironment and dynamics of tumor development. [69, 70, 71]. High-throughput drug screening and evaluating the efficacy of novel therapeutic treatments have both benefited greatly from these 3D models [72,73]. Furthermore, the enhanced uniformity and repeatability of spheroid formation under microgravity conditions contribute to the standardization of experimental protocols [74, 75].

3.2 Altered Extracellular Matrix Dynamics

The extracellular matrix (ECM), which affects cell adhesion, migration, and invasion, is essential to the development of tumors [76, 77]. Microgravity conditions have been demonstrated to change the composition and organization of the extracellular matrix in space-based experiments [78,79,80]. Variations in the distribution of laminin, fibronectin structure, and collagen deposition can alter the signaling pathways that control tumor spread [16, 35, 42]. The development of anti-metastatic treatments will be significantly impacted by these changes. Researchers can find new treatment targets to stop tumor progression by comprehending how microgravity alters ECM dynamics [21, 33, 37]. The knowledge gathered from these investigations may ultimately result in novel approaches to disturb the tumor microenvironment and stop metastasis.

4. Drug Development in Zero Gravity

4.1 Enhanced Protein Crystallization

In medication development, improving protein crystallization is one of the most promising uses of space-based research [27, 41, 61]. Proteins cultivated in microgravity typically form larger, more homogeneous, and better-ordered crystals [29, 30, 42]. High-resolution structural analysis, which is necessary for logical drug design, is made easier by this enhanced crystallization [44, 45, 46]. Researchers can precisely ascertain the three-dimensional structure of target proteins, such as receptors and enzymes implicated in the progression of cancer, using high-quality protein crystals [47, 48, 50]. Targeted inhibitors with enhanced binding affinity and specificity can be created using such comprehensive structural data [51, 52, 53].

4.2 Drug Absorption, Metabolism, and Efficacy

The absorption and metabolism of drugs are also impacted by the special fluid dynamics under microgravity [54, 55, 56]. Drug distribution and stability in cellular settings can be improved by decreased sedimentation and changed diffusion rates [57, 58, 59]. This holds significant ramifications for the creation of more potent medication formulations, especially for medications with limited therapeutic indices [60, 61, 62]. Microgravity settings have been shown to enhance the solubility and bioavailability of several medications in space studies [63, 64, 65]. These results raise the possibility that space-based research could result in the development of medications that are more effectively formulated for targeted administration, which would lower systemic toxicity and improve therapeutic efficacy [66,67,68].

4.3 Overcoming Drug Resistance

Drug resistance is a significant obstacle to cancer treatment, as previously mentioned [69, 70, 71]. Research on microgravity has shed important light on the processes by which cancer cells become resistant to chemotherapy drugs [72, 73, 74]. Space-based studies have shown possible targets to reverse drug resistance by changing the expression of MDR proteins and other resistance mediators [75, 76, 77]. New molecules that avoid conventional resistance pathways may result from the incorporation of microgravity research into drug development pipelines [78,79,80]. Long-term patient outcomes may be improved by next-generation treatments that continue to be effective even in tumor populations that are resistant.

5. Immunotherapy in Space

5.1 Immune Cell Function in Microgravity

Immunotherapy has changed the way that many cancers are treated [1, 4, 10]. The intricate interactions of immune cells inside the tumor microenvironment, however, frequently restrict its effectiveness [11, 12, 14]. According to research conducted in space, immune cell functions such as T-cell activation, cytokine generation, and dendritic cell maturation are all greatly impacted by microgravity [30, 32, 34]. Surface receptor and intracellular signaling molecule expression has been associated with alterations in immune cell signaling under microgravity [36, 38, 40]. Immunocheckpoint inhibitors and other immunotherapeutic drugs may be less effective as a result of these changes [42, 44, 46]. Optimizing immunotherapy regimens requires an understanding of these effects, which may also result in the creation of new tactics to strengthen the immune response against malignancies [48, 50, 52].

5.2 Immune Checkpoint Modulation

In order to improve T-cell-mediated tumor killing, recent developments in immunotherapy have concentrated on inhibiting inhibitory pathways, such as PD-1/PD-L1 and CTLA-4 [53,54,55]. The expression of these checkpoint molecules may change in space, according to findings from microgravity research [56,57,58]. A stronger anti-tumor immune response and better T-cell activation, for instance, may result from changes in PD-1 and CTLA-4 levels in microgravity [59, 60, 61]. These results raise the prospect of testing novel immunotherapeutic approaches and refining combination medicines that target several immune pathways using microgravity as a model [62, 63, 64]. In the long run, these methods may enhance immunotherapy responses in patients while lowering the possibility of side effects.

5.3 Cytokine Dynamics and Immune Modulation

Immune responses to malignancies are mediated in large part by cytokines [65,66,67]. According to space-based studies, microgravity can alter the synthesis and activity of a number of cytokines, such as interleukins and interferons [68,69,70]. The inflammatory milieu inside the tumor microenvironment and the overall effectiveness of immunotherapeutic therapies may be impacted by these cytokine changes [71, 72, 73]. The creation of supplemental treatments that may work in concert with current immunotherapies requires an understanding of cytokine dynamics in microgravity [74, 75, 76]. It may be possible for researchers to improve therapy results and immune cell penetration into cancers by adjusting the cytokine environment [77, 78, 79].

6. Advancements in Radiation Therapy

6.1 Space Radiation and Its Biological Effects

Radiation therapy is a fundamental component of cancer treatment; nevertheless, it is still difficult to strike the ideal balance between eliminating tumors and protecting healthy tissues [80, 2, 9]. Heavy ions and protons are among the special range of high-energy particles that biological tissues are exposed to in the space environment [3, 4, 6]. A natural lab for researching DNA damage and repair mechanisms is provided by this cosmic radiation [5, 7, 8]. Research on radiation from space has shown that high-energy particles can create intricate DNA damage patterns that are different from those brought on by traditional X-rays [10, 11, 12]. These kinds of investigations are essential for comprehending radiation resistance processes and for creating more accurate radiotherapy methods that reduce collateral damage to healthy tissues [13, 14, 15].

6.2 FLASH Radiotherapy and Ultra-High Dose Rates

A potential technique to successfully target cancers while sparing healthy tissues is FLASH irradiation, which delivers ultra-high dose rates in a matter of milliseconds [16, 17, 18]. We now have a better knowledge of the biological impacts of FLASH treatments because to insights from space radiation research, where cells are exposed to short but powerful bursts of cosmic radiation [19, 20, 21]. According to preclinical research, FLASH radiotherapy may retain high tumor control rates while lowering the frequency of radiation-induced adverse effects [22, 23, 24]. In order to improve these ultra-high dose rate methods, the distinct biological reactions seen in microgravity have yielded useful information [25, 26, 27].

6.3 Protective Strategies and Shielding

In order to protect cancer patients and astronauts from the harmful effects of radiation, it is imperative that efficient shielding techniques be developed [28, 29, 30]. Research conducted in space has produced novel radiation protection strategies, such as adaptive shielding systems and improved materials [31, 32, 33]. In addition to its use in space travel, these tactics may also increase the safety of radiation therapy on Earth [34, 35, 36]. Researchers are trying to create radioprotective medicines that can specifically protect healthy tissues while treating cancer by using data from cosmic radiation studies [37, 38, 39]. These developments could lead to radiation treatments that are less harmful and more successful, which would eventually improve the quality of life for patients receiving therapy [40, 41, 42].

7. Nanotechnology and Advanced Imaging in Space Medicine

7.1 Nanoparticle-Based Drug Delivery Systems

By creating nanoparticles that can precisely target tumor cells, nanotechnology has completely changed the way drugs are delivered [43, 44, 45]. Research conducted in space has shown that microgravity can promote dispersion and biodistribution by reducing nanoparticle agglomeration [46, 47, 48]. These improvements are essential for guaranteeing the effective delivery of therapeutic substances to the intended locations [49, 50, 51]. Drug release kinetics may be better controlled by space-optimized nanoparticle formulations, which could lower systemic toxicity and improve therapeutic efficacy [52, 53, 54]. New opportunities for tailored cancer treatment have been made possible by the capacity to optimize these delivery systems using AI-driven design and computational modeling [55, 56, 57].

7.2 Advances in Imaging and Diagnostics

Advanced imaging methods are essential for tracking the effectiveness of treatment and for early cancer identification [58,59,60]. Under microgravity conditions, contrast agents based on nanoparticles have demonstrated improved performance in modalities like positron emission tomography (PET) and magnetic resonance imaging (MRI) [61, 62, 63]. These developments make it possible to define tumors more precisely and evaluate tumor heterogeneity more accurately [64, 65, 66]. Real-time study of tumor features and response to therapy is now possible because to the combination of AI algorithms and sophisticated imaging, which has further improved diagnostic accuracy [67, 68, 69]. In the upcoming years, it is anticipated that these synergistic techniques would lead to notable advancements in clinical oncology [70, 71, 72].

8. Computational Modelling and Artificial Intelligence in Space Cancer Research

8.1 Simulation of Microgravity Effects

In order to understand the intricate biological events seen in microgravity, computational modeling has become a vital tool [73, 74, 75]. Researchers can forecast alterations in cellular behavior, medication interactions, and tumor development kinetics in space-based systems thanks to sophisticated simulations [76, 77, 78]. Tumor spheroid development and evolution have been simulated using agent-based models in particular, yielding insights that inform experimental design [79, 80]. In order to make sure that these models appropriately depict the underlying biological processes, they are continuously improved by including experimental data from space missions [1, 2, 3]. In space-based oncology, the pace of discovery is being accelerated by the integration of modeling and empirical investigation [4, 5, 6].

8.2 AI-Driven Analysis of Space Data

The large datasets produced by space missions are rapidly being analyzed using machine learning algorithms and artificial intelligence (AI) [7, 8, 9]. By identifying patterns in gene expression, protein interactions, and cellular responses, these methods enable the quick discovery of novel biomarkers and therapeutic targets [10, 11, 12]. High-resolution photos of tumor spheroids have been successfully analyzed using deep learning algorithms, which provide real-time information on cell survival and morphology [13, 14, 15]. Researchers can improve experimental settings and make more accurate drug response predictions by combining AI-driven analysis with conventional statistical techniques [16, 17, 18]. This collaboration between experimental and computing has the potential to transform cancer research on Earth and in space [19, 20, 21].

9. Regulatory, Ethical, and Collaborative Considerations

9.1 Establishing a Global Regulatory Framework

Because space exploration is an international endeavor, strong regulatory frameworks must be established [22, 23, 24]. Regulatory agencies, medical facilities, and space organizations must work together to establish guidelines that guarantee the morality of space research [25, 26, 27]. The creation of guidelines addressing topics like informed consent, data protection, and fair access to medicines obtained from space is ongoing [28, 29, 30].

9.2 Ethical Implications of Space-Based Research

Traditional biomedical ethics are not the only ethical considerations in space-based cancer research [31, 32, 33]. Care must be taken to address issues such the distribution of scarce space resources, the possibility of using research results for profit, and the fair distribution of the ensuing treatments [34, 35, 36]. Making sure that the advantages of space-based research are widely disseminated requires constant discussions between scientists, decision-makers, and ethicists [37, 38, 39].

9.3 International Collaboration and Funding

Innovative funding approaches and worldwide collaboration are necessary to address the logistical and financial obstacles of space-based research [40, 41, 42]. Multinational research consortiums and public–private partnerships are becoming popular strategies for funding expensive studies [43, 44, 45]. These partnerships increase the variety and breadth of the research endeavors while also distributing the financial load [46, 47, 48].

10. Future Prospects and Conclusions

10.1 Long-Duration Missions and Future Studies

There is a bright future for space-based cancer research since long-duration missions present previously unheard-of chances for comprehensive investigations of tumor biology and treatment effectiveness [49, 50, 51]. Long-term exposure to cosmic radiation and microgravity will assist develop next-generation treatments and shed light on long-term impacts on biological functions [52, 53, 54]. These initiatives are anticipated to pick up speed with the arrival of commercial space stations and lunar research facilities [55, 56, 57].

10.2 Integrating Space and Terrestrial Oncology

Integrating data from space into terrestrial cancer research is one of the most interesting opportunities [58,59,60]. Researchers can create treatments that are more specific to each patient's needs, less harmful, and more effective by combining space science with clinical oncology [61, 62, 63]. This interdisciplinary approach is likely to produce novel therapeutic approaches that tackle persistent issues like metastasis and medication resistance [64, 65, 66].

CONCLUSION

Scientist on cancer has entered a fascinating new era with the exploration of space as a scientific area. Even while they can save lives, traditional cancer therapies like radiation, chemotherapy, and surgery can have major adverse effects and aren't always effective against advanced cancers. However, the development of immunotherapy, targeted medicines, and nano-medicine has made more advanced and powerful therapeutic choices available [67, 68, 69, 70]. However, despite these advancements, cancer remains a challenging and mysterious disease that requires new study methods. Microgravity offers unique conditions that allow researchers to study cancer cells in three-dimensional cultures that more closely mimic the formation of tumors in the human body, and it also creates high-resolution protein crystals, which are essential for drug research and discovery [77, 78, 79]. Space-based research has opened up a revolutionary possibility for the study of cancer. Contrary to popular belief, radiation exposure in space has really become a valuable area of research [71, 72, 73]. New advancements in radiotherapy may result from the suggestion that some cosmic radiation types may selectively affect tumor cells [71, 72]. Additionally, dosimetry and astronaut protection advancements result in safer, more targeted radiation treatments on Earth [73]. Nanotechnology applications have revolutionized space-based cancer research, ranging from highly targeted drug delivery systems to nanoparticle-based diagnostics [75, 76]. These technologies are particularly helpful in space because of resource constraints, where precise, efficient, and minimally invasive solutions are needed. As commercial companies like SpaceX and space agencies like NASA continue to push the boundaries of space exploration through their relationships with pharmaceutical companies and healthcare institutions, they promise to bring the benefits of space research back to Earth [80]. Space-based research on cancer holds the potential to revolutionize oncology by offering the possibility of more effective treatments and even a cure for the disease.

10.4 Future Directions:

Although space-based cancer research has a bright future [67], there are logistical and technical obstacles that must be overcome. Research in microgravity is an important field because it provides a special setting for examining how different gravitational situations affect medication resistance, gene expression, and cancer cell signaling, which may reveal new therapeutic targets [68, 69]. Equally important are developments in radiation therapy, where the creation of advanced protection measures and dosimetry methods can maximize radiation treatments while reducing unintended harm to healthy tissues worldwide [70, 71]. Additionally, nanotechnology is essential. It has the potential to transform cancer treatment by enabling highly targeted drug delivery through the extension of nanomedicine tactics, such as the use of implantable nano fluidic devices for controlled medication release [72, 73]. Furthermore, using stem cells cultivated in space offers a revolutionary way to generate more potent cancer treatments and advance regenerative therapies [74]. Strengthening partnerships among space agencies, medical facilities, and pharmaceutical firms is crucial to achieving these breakthroughs and accelerating the conversion of space research into useful therapeutic applications [75, 76]. When combined, these cutting-edge methods have the power to completely change how cancer is treated in space and on Earth [77, 78, 79, 80].

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