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Review

Artificial Intelligence and Telemedicine Beyond Earth: A Systematic Review of Biomedical Innovations from Space to Planetary Healthcare

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SUMMARY

Artificial intelligence (AI) and telemedicine are rapidly transforming healthcare delivery, particularly in remote and resource-limited environments. In human space exploration, these technologies play a crucial role by enabling autonomous clinical decision-making, continuous physiological monitoring, and early detection of health risks during missions far from Earth. This study presents a systematic review of AI-driven and telemedicine innovations developed for space medicine and examines their translational impact on terrestrial healthcare systems. Following PRISMA 2020 guidelines, literature searches were conducted in PubMed, Scopus, Web of Science, and the NASA Technical Reports Server for studies published between 2010 and 2025. From 864 identified records, 72 studies met the inclusion criteria. The analysis revealed three main domains of innovation: AI-assisted diagnostic systems, autonomous telemedicine platforms, and wearable biosensing technologies integrated with advanced data analytics. These technologies demonstrate significant potential to strengthen digital health infrastructures, improve healthcare accessibility, and support resilient planetary healthcare systems capable of operating in extreme environments.

KEYWORDS

Artificial Intelligence; Telemedicine; Space Medicine; Planetary Healthcare; Biomedical Innovation; Generative AI.

INTRODUCTION

Human space exploration has historically driven major technological innovations that later transformed everyday life on Earth. In recent decades, biomedical research conducted in space environments has emerged as a particularly fertile field for technological advancement. The unique physiological challenges posed by microgravity, radiation exposure, confinement, and communication delays require novel healthcare strategies capable of functioning autonomously in extreme environments. As a result, space agencies such as the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and several international research institutions have invested heavily in developing advanced biomedical technologies designed to maintain astronaut health during long-duration missions (NASA, 2023).

Among these innovations, artificial intelligence (AI) and telemedicine systems have gained particular prominence. Artificial intelligence has rapidly expanded its role in modern medicine by enabling automated diagnostic analysis, predictive modeling, and intelligent decision-support systems capable of processing large volumes of biomedical data (Topol, 2019). Telemedicine, on the other hand, has transformed the delivery of healthcare services by allowing medical expertise to reach remote or underserved populations through digital communication technologies (Wootton, 2012).

In the context of spaceflight medicine, these technologies are not merely supportive tools but essential components of mission safety. Long-duration space missions often involve significant communication delays between spacecraft and Earth-based medical teams, which means that astronauts must rely on onboard systems capable of assisting in diagnosis, monitoring, and treatment decisions. Consequently, AI-driven medical platforms and autonomous telemedicine systems have become critical components of modern space medicine research (Antonsen et al., 2020).

Despite the growing body of research in space medicine, relatively little effort has been made to systematically synthesize how these technologies influence terrestrial healthcare systems. In recent years, scholars have increasingly recognized the concept of **"planetary healthcare,"** which emphasizes the integration of technological innovations developed in extreme environments with global health systems on Earth (Gómez et al., 2021). Space-derived biomedical technologies have demonstrated considerable potential in areas such as remote surgery, digital diagnostics, wearable monitoring systems, and predictive health analytics.

This study seeks to address this gap by systematically reviewing the scientific literature on artificial intelligence and telemedicine applications developed for space missions and evaluating their translational impact on terrestrial healthcare systems. Specifically, the review examines how innovations originally designed for astronaut health management have contributed to the evolution of digital healthcare infrastructures capable of operating in remote, resource-limited, or extreme conditions.

LITERATURE BACKGROUND AND THEORETICAL FOUNDATIONS

TThe intersection of artificial intelligence, telemedicine, and space medicine represents a rapidly evolving field of interdisciplinary research. Advances in biomedical engineering, computational sciences, and aerospace medicine have created new opportunities for developing healthcare technologies capable of operating in extreme and remote environments. Understanding the theoretical foundations of these innovations requires examining the evolution of digital health technologies, the emergence of AI-driven medical systems, and the unique biomedical challenges associated with human spaceflight.

Artificial intelligence has increasingly become a central component of modern healthcare systems. The application of machine learning and advanced data analytics has enabled the development of diagnostic tools capable of analyzing complex biomedical datasets with a level of precision comparable to, and sometimes exceeding, human clinicians. As Topol (2019) argues, AI-driven medicine represents a fundamental shift in the way healthcare information is processed, allowing for faster and more accurate interpretation of medical imaging, physiological signals, and genomic data. These capabilities are particularly valuable in environments where access to medical specialists is limited, such as remote regions on Earth or spacecraft operating far from terrestrial medical support.

The theoretical foundations of AI in medicine are rooted in the concept of **clinical decision-support systems**, which integrate computational algorithms with clinical knowledge to assist healthcare professionals in diagnosis and treatment planning. Early decision-support systems relied primarily on rule-based models; however, recent advances in deep learning and generative AI have significantly expanded the predictive and analytical capabilities of these systems (Esteva et al., 2017). In the context of space medicine, AI-based decision-support tools are particularly important because astronauts must often rely on autonomous systems to manage medical conditions during long-duration missions.

Telemedicine represents another key technological pillar underlying modern digital healthcare systems. Originally developed to extend medical expertise to remote geographic locations, telemedicine has evolved into a comprehensive digital healthcare infrastructure that integrates video communication, remote diagnostics, wearable monitoring technologies, and electronic health records. According to Wootton (2012), telemedicine has become an essential mechanism for addressing healthcare disparities by improving access to medical services in underserved communities. The COVID-19 pandemic further accelerated the adoption of telemedicine technologies worldwide, demonstrating their capacity to maintain healthcare delivery even under conditions of restricted mobility and limited healthcare resources.

Space exploration provides a unique environment for the development of advanced telemedicine systems. Unlike terrestrial telemedicine applications, medical support for astronauts must account for communication delays, limited onboard medical equipment, and the absence of specialized medical personnel. These constraints have motivated the development of autonomous telemedicine systems capable of providing diagnostic guidance and treatment recommendations without real-time communication with Earth-based medical teams (Antonsen et al., 2020). Such systems combine digital communication technologies with AI-based medical decision-support tools, creating hybrid healthcare platforms capable of operating under extreme conditions.

The biomedical challenges associated with spaceflight further underscore the importance of these technologies. Exposure to microgravity induces significant physiological changes in the human body, including cardiovascular deconditioning, bone mineral density loss, immune system alterations, and fluid redistribution (Caruso et al., 2021). Monitoring these physiological changes requires continuous collection and analysis of biomedical data, which has led to the development of sophisticated wearable biosensing systems capable of measuring multiple physiological parameters simultaneously. These systems often integrate AI-based analytics platforms that can identify early signs of physiological stress or disease.

Another theoretical concept relevant to this research is the emerging framework of **planetary health and planetary healthcare**. Planetary health recognizes the interconnected relationship between human health, technological development, and the broader planetary environment (Whitmee et al., 2015). Extending this concept to the context of space exploration, planetary healthcare refers to the integration of medical technologies designed for extraterrestrial environments with terrestrial healthcare systems. This framework emphasizes the bidirectional flow of technological innovation between space research and global health systems.

Space medicine has historically contributed to numerous technological advances that later found widespread applications on Earth. For example, medical imaging technologies, remote monitoring devices, and advanced prosthetic systems have all benefited from research conducted within aerospace medicine programs. Recent studies suggest that the next generation of healthcare innovations may emerge

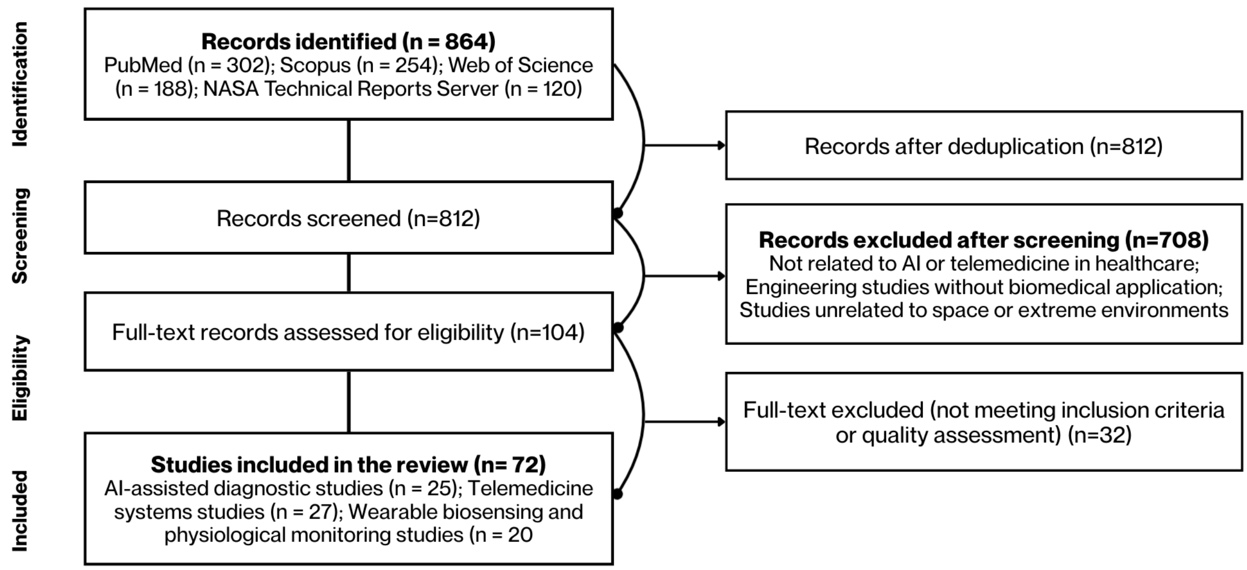

Figure 1. PRISMA Flow Diagram of the Literature Selection Proces

PRISMA 2020 flow diagram illustrating the identification, screening, eligibility assessment, and inclusion of studies in the systematic review of artificial intelligence and telemedicine applications in space medicine and planetary healthcare.

from the integration of artificial intelligence with biomedical systems designed for long-duration space missions (Antonsen et al., 2020). These technologies have the potential to support autonomous healthcare systems capable of functioning independently in remote or resource-constrained environments.

In addition to technological innovation, ethical and governance considerations are increasingly recognized as important components of AI-driven healthcare systems. Floridi et al. (2018) emphasize that responsible AI development must address issues such as algorithmic transparency, fairness, and data privacy. These concerns are particularly relevant in the context of autonomous healthcare systems, where AI algorithms may play a central role in clinical decision-making. As healthcare systems become more reliant on digital technologies, establishing ethical frameworks and regulatory guidelines will be essential to ensure safe and equitable implementation.

Overall, the literature demonstrates that the convergence of artificial intelligence, telemedicine, and space medicine represents a transformative frontier in biomedical science. Theoretical models of digital healthcare increasingly emphasize autonomy, connectivity, and predictive analytics as key characteristics of future healthcare systems. By examining these developments within the context of space exploration, researchers can gain valuable insights into how emerging technologies may shape the evolution of global healthcare infrastructures.

METHODS

Review Design and Research Framework

This systematic review was conducted following the **Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020)** (Figure 1) guidelines, which provide a structured framework for conducting and reporting systematic reviews in biomedical research (Page et al., 2021). The review protocol was designed to identify peer-reviewed publications addressing the intersection of artificial intelligence, telemedicine, and space medicine between 2010 and 2025.

The literature search was performed across four major scientific databases: PubMed, Scopus, Web of Science, and the NASA Technical Reports Server (NTRS). These databases were selected to ensure comprehensive coverage of both biomedical and aerospace research literature.

The literature search was conducted using a structured combination of keywords related to artificial intelligence, telemedicine, and space medicine. Boolean operators were applied to integrate the primary technological domains and biomedical contexts relevant to healthcare in extreme environments and spaceflight conditions. The search strategy was designed to capture studies addressing both technological development and clinical applications of digital health systems in space exploration and their translational relevance for terrestrial healthcare systems. The primary search string included the following terms:

("artificial intelligence" OR "machine learning" OR "generative AI") AND ("telemedicine" OR "remote healthcare" OR "digital health") AND ("space medicine" OR "spaceflight health" OR "microgravity" OR "astronaut health") AND ("diagnostics" OR "physiological monitoring" OR "predictive medicine" OR "clinical decision support")

This search approach enabled the identification of interdisciplinary research addressing the intersection between biomedical space science, digital health technologies, and emerging AI-driven healthcare systems designed for remote or resource-limited environments.

All identified records were exported into the Rayyan QCRI systematic review platform, which facilitated collaborative screening and data extraction (Ouzzani et al., 2016). Duplicate records were removed prior to screening. Two independent reviewers conducted the initial screening of titles and abstracts to determine relevance to the study objectives. Articles that passed the initial screening were subsequently subjected to full-text review to confirm eligibility.

Studies were included in the review if they met three primary criteria: (1) they described the use of artificial intelligence or telemedicine in spaceflight or extreme environments, (2) they presented biomedical or clinical implications for human health, and (3) they were published in peer-reviewed journals. Studies that focused exclusively on engineering systems without biomedical relevance or lacked sufficient methodological detail were excluded.

Quality assessment of included studies was conducted using a modified appraisal framework based on the **Mixed Methods Appraisal Tool (MMAT)**, which allows evaluation of both quantitative and qualitative research designs (Hong et al., 2018). Data extracted from each study included the type of technology investigated, the medical application, the environment in which the technology was tested, and its potential applicability to terrestrial healthcare systems.

RESULTS

The systematic search initially identified 864 records across the four databases. After removing duplicates and conducting title and abstract screening, 104 studies were selected for full-text review. Of these, 72 met the final inclusion criteria and were included in the qualitative synthesis.

Analysis of the selected studies revealed three dominant domains of technological innovation: artificial intelligence–assisted diagnostic systems, autonomous telemedicine platforms, and wearable biosensing technologies integrated with advanced data analytics (Table 1).

Table 1. Distribution of Studies by Technology Domain

Domain	Number of Studies	Percentage
AI-assisted diagnostics	25	34.7%
Telemedicine systems	27	37.5%
Biosensing and wearable monitoring	20	27.8%

AI-Assisted Diagnostics

A substantial portion of the reviewed studies focused on the development of AI-driven diagnostic tools capable of operating under microgravity conditions. These systems often rely on machine learning algorithms trained to analyze medical imaging data such as ultrasound scans, retinal images, or musculoskeletal assessments. Research conducted aboard the International Space Station has demonstrated that AI-assisted ultrasound systems can help astronauts perform complex diagnostic procedures without the need for direct supervision from medical specialists on Earth (Cao et al., 2022).

These technologies have significant implications for terrestrial healthcare systems, particularly in remote regions where access to specialized medical expertise is limited. AI-assisted diagnostic tools developed for space missions can help general practitioners or healthcare workers perform sophisticated diagnostic evaluations with minimal training.

Autonomous Telemedicine Systems

Another major domain of innovation identified in the literature involves autonomous telemedicine systems capable of functioning under delayed communication conditions. In deep-space missions, communication delays between spacecraft and Earth may reach up to 20 minutes, making real-time medical consultations impractical. To address this challenge, researchers have developed telemedicine platforms that incorporate decision-support algorithms capable of guiding astronauts through diagnostic and treatment procedures (Antonsen et al., 2020).

These systems have since been adapted for terrestrial applications such as remote surgery, disaster response medicine, and rural healthcare networks. In particular, robotic surgical systems originally designed for teleoperated procedures in space environments have contributed to the development of advanced remote surgical platforms used in hospitals worldwide (Haidegger et al., 2017).

Wearable Biosensing Systems

Wearable biosensing technologies represent the third major domain identified in this review. Astronaut health monitoring requires continuous measurement of physiological parameters such as heart rate variability, respiratory patterns, body temperature, and metabolic activity. To meet these needs, researchers have developed advanced wearable monitoring systems capable of collecting real-time physiological data in space environments (Caruso et al., 2021).

Recent developments have integrated generative AI algorithms into these systems, enabling predictive health monitoring capable of identifying physiological anomalies before symptoms appear. These predictive models are now being applied to terrestrial healthcare settings, particularly in the management of chronic diseases such as cardiovascular disorders and diabetes.

DISCUSSION

The findings of this systematic review highlight the profound role that space medicine research plays in accelerating technological innovation in healthcare systems on Earth. Space missions represent one of the most demanding environments for human health management, where medical interventions must often be performed autonomously, with limited resources and delayed communication with ground-based medical teams. These constraints create a unique research environment that encourages the development of advanced digital health technologies capable of operating independently and reliably under extreme conditions. As a result, space medicine has become an important experimental platform for the development of autonomous medical systems, many of which are now being adapted to terrestrial healthcare applications.

One of the most significant insights emerging from the reviewed literature is the growing importance of artificial intelligence as a central component of space health management. AI-driven diagnostic systems have demonstrated considerable potential in assisting astronauts with medical decision-making, particularly when direct access to medical specialists is unavailable. Machine learning algorithms capable of interpreting medical images, analyzing physiological data, and predicting health risks have shown promising results in experimental studies conducted aboard the International Space Station and other simulated space environments (Cao et al., 2022; Antonsen et al., 2020). These technologies reduce the cognitive burden on astronauts and allow for faster identification of potential medical issues, which is critical during long-duration missions where timely intervention may determine mission success.

The implications of these technologies extend well beyond the context of space exploration. Many of the AI-based diagnostic tools developed for space medicine have been adapted to support healthcare delivery in remote or underserved areas on Earth. In rural regions, for example, AI-assisted diagnostic platforms can enable healthcare professionals with limited specialized training to perform complex medical assessments with greater accuracy. Similar technologies have been deployed in humanitarian missions, disaster response scenarios, and telehealth programs aimed at expanding healthcare access to geographically isolated communities (Topol, 2019).

Another important dimension revealed by this review concerns the development of autonomous telemedicine systems. Unlike traditional telemedicine platforms used on Earth, space telemedicine must function under conditions of communication delay and limited bandwidth. For missions beyond low Earth orbit, communication delays between spacecraft and Earth may range from several minutes to more than twenty minutes. These constraints necessitate telemedicine platforms capable of supporting asynchronous medical consultation and providing real-time clinical guidance through embedded decision-support algorithms (Antonsen et al., 2020).

Research conducted by NASA and other space agencies has demonstrated that such systems can significantly improve the ability of astronauts to diagnose and manage medical conditions during missions. Autonomous telemedicine frameworks combine medical knowledge databases, diagnostic algorithms, and interactive guidance systems to assist astronauts in performing medical procedures with minimal external supervision. These systems are now influencing the development of next-generation telehealth platforms on Earth, particularly in contexts where healthcare providers must operate in resource-constrained environments.

The review also highlights the growing role of wearable biosensing technologies in both space medicine and terrestrial healthcare. Continuous physiological monitoring is essential during space missions due to the complex physiological changes induced by microgravity, including cardiovascular deconditioning, bone density loss, and fluid redistribution within the body (Caruso et al., 2021). Wearable monitoring systems developed for astronauts, such as smart garments and biosensor-equipped medical devices, enable real-time collection of physiological data without interfering with daily activities.

The integration of artificial intelligence with wearable monitoring systems has further expanded the capabilities of these technologies. AI-driven analytics platforms can analyze large volumes of physiological data to identify patterns that may indicate the early onset of health problems. Predictive health monitoring systems based on these technologies are now being implemented in terrestrial healthcare settings to support the management of chronic diseases such as heart failure, diabetes, and respiratory disorders. In this context, space medicine research has contributed significantly to the advancement of personalized and preventive healthcare models.

The concept of **planetary healthcare** provides a useful framework for understanding the broader implications of these technological developments. Planetary healthcare emphasizes the interconnected nature of health systems across terrestrial and extraterrestrial environments and recognizes that innovations developed for space exploration may provide valuable solutions to global healthcare challenges (Gómez et al., 2021). Technologies capable of functioning reliably in extreme environments are particularly valuable in addressing healthcare needs in remote regions, disaster zones, and areas with limited medical infrastructure.

Despite the promising potential of AI-driven healthcare technologies, several challenges remain regarding their implementation and governance. One of the most pressing concerns involves the ethical implications of autonomous medical decision-making systems. Artificial intelligence algorithms used in clinical decision support must be transparent, interpretable, and subject to rigorous validation to ensure that they produce reliable and unbiased results. Concerns related to algorithmic bias, data privacy, and accountability in automated clinical decision-making have been widely discussed in recent years (Floridi et al., 2018). These issues become even more complex in the context of space missions, where autonomous systems may need to make critical medical decisions without immediate human oversight.

Regulatory frameworks for AI-based healthcare technologies must therefore evolve alongside technological innovation. International collaboration between regulatory agencies, space agencies, and healthcare institutions will be essential to establish guidelines for the safe and ethical deployment of AI-driven medical systems. Furthermore, interdisciplinary research efforts involving biomedical scientists, aerospace engineers, computer scientists, and public health experts will play a key role in advancing this field.

Another important research direction concerns the scalability of space-derived healthcare technologies. While many of the technologies identified in this review show considerable promise, their widespread adoption in terrestrial healthcare systems will require significant investment in infrastructure, training, and regulatory adaptation. Future studies should focus on evaluating the cost-effectiveness and long-term impact of implementing these technologies in different healthcare settings.

Finally, the increasing involvement of private space companies in human spaceflight may accelerate the pace of innovation in biomedical space research. Commercial space missions and emerging lunar and Martian exploration programs will likely generate new opportunities for testing advanced healthcare technologies in extreme environments. These developments may further strengthen the connection between space exploration and global healthcare innovation.

Overall, the findings of this review reinforce the idea that space medicine is not only essential for supporting human exploration beyond Earth but also serves as a powerful catalyst for technological advancement in healthcare. By addressing the unique medical challenges of spaceflight, researchers are developing innovative healthcare solutions that have the potential to transform medical practice on Earth and contribute to the development of more resilient and equitable healthcare systems worldwide.

CONCLUSION

This systematic review demonstrates that biomedical technologies originally developed for space exploration are playing an increasingly significant role in shaping the future of healthcare systems on Earth. Artificial intelligence, telemedicine platforms, and wearable biosensing technologies designed to support astronaut health during space missions have evolved into powerful tools capable of transforming modern healthcare infrastructures. These innovations illustrate how research conducted in extreme environments can accelerate the development of resilient medical systems capable of operating in remote, resource-limited, or high-risk conditions.

The evidence analyzed in this review indicates that the integration of AI-driven diagnostics, autonomous telemedicine systems, and continuous physiological monitoring technologies has substantially expanded the possibilities for predictive and personalized healthcare. Technologies initially created to address the challenges of microgravity, communication delays, and medical autonomy in space missions are now being adapted for terrestrial healthcare contexts, including rural medicine, disaster response, telepsychiatry, and chronic disease management. As a result, space medicine has become a critical testbed for developing healthcare solutions that can operate effectively in environments where traditional medical infrastructures are limited or unavailable.

Furthermore, the convergence of artificial intelligence and space medicine introduces a new paradigm in healthcare innovation that may be described as **planetary healthcare**. This concept reflects the growing recognition that technological advances emerging from extraterrestrial research environments can provide scalable solutions to global health challenges. By integrating advanced data analytics, wearable monitoring systems, and autonomous clinical decision-support tools, planetary healthcare systems have the potential to enhance healthcare accessibility, improve diagnostic accuracy, and support preventive medicine on a global scale.

However, the increasing reliance on AI-driven medical systems also raises important ethical, regulatory, and governance considerations. Issues related to algorithmic transparency, patient data privacy, clinical accountability, and the safe deployment of autonomous medical systems must be carefully addressed to ensure responsible adoption of these technologies. As healthcare systems become more dependent on digital infrastructure, interdisciplinary collaboration between biomedical researchers, space agencies, healthcare providers, and regulatory institutions will be essential.

Future research should focus on validating these technologies in diverse clinical contexts and developing standardized frameworks for integrating space-derived medical innovations into global healthcare systems. Additionally, expanding collaboration between space medicine programs and public health institutions may accelerate the translation of emerging technologies into scalable healthcare solutions capable of addressing the needs of both terrestrial and extraterrestrial populations.

Ultimately, the intersection of artificial intelligence, telemedicine, and space medicine represents a transformative frontier in biomedical science. By leveraging the unique challenges of space exploration as a catalyst for innovation, researchers can develop healthcare technologies that not only ensure the safety of future astronauts but also improve the quality, accessibility, and resilience of healthcare systems worldwide.

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DECLARATION OF INTERESTS

The author state no conflict of interest.

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