

www.pharmaerudition.org

ISSN: 2249-3875



# International Journal of Pharmaceutical Erudition

Research for Present and Next Generation

**MAY 2026**

Vol: 16 Issue:01  
(47-58)





**Review Article**

**INTERVENTION AND TREATMENT OF HIV/AIDS THOROUGH NANOTECHNOLOGY**

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Human Immunodeficiency Virus (HIV) infection and its advanced stage, Acquired Immuno-deficiency Syndrome (AIDS), continue to represent a major global public health challenge despite significant progress in therapeutic interventions. Since the introduction of antiretroviral therapy (ART), particularly Highly Active Antiretroviral Therapy (HAART), the morbidity and mortality associated with HIV/AIDS have been substantially reduced. However, these conventional therapeutic strategies are not curative and are associated with several limitations, including drug resistance, systemic toxicity, poor bioavailability, limited penetration into viral reservoirs, and the requirement for lifelong adherence. These challenges necessitate the exploration of innovative and more effective treatment approaches. In this context, nanotechnology has emerged as a promising and transformative tool in the field of HIV/AIDS intervention and treatment.

Nanotechnology involves the design, development, and application of materials at the nanoscale, typically ranging from 1 to 100 nanometers, where unique physicochemical properties such as enhanced surface area, improved reactivity, and tunable surface functionalities can be exploited for biomedical applications. In HIV therapeutics, nanotechnology offers novel strategies for targeted drug delivery, improved pharmacokinetics, reduced toxicity, and enhanced therapeutic efficacy. Nanocarriers can be engineered to deliver antiretroviral drugs directly to infected cells and tissues, thereby minimizing off-target effects and maximizing drug concentration at the site of infection. A variety of nanocarrier systems have been investigated for HIV treatment, including liposomes, polymeric nanoparticles, dendrimers, solid lipid nanoparticles, nanomicelles, and inorganic nanoparticles such as gold and silver nanoparticles. These nanosystems differ in their composition, structure, and functional capabilities, allowing for flexibility in drug encapsulation and delivery. Liposomes, for instance, are biocompatible vesicles capable of carrying both hydrophilic and hydrophobic drugs, while polymeric nanoparticles offer controlled and sustained drug release. Dendrimers, with their highly branched architecture, provide high drug-loading capacity and can also function as antiviral agents. Lipid-based nanoparticles, particularly lipid nanoparticle systems, have gained considerable attention for their ability to deliver nucleic acids, including RNA-based therapeutics. One of the most significant advantages of nanotechnology in HIV treatment is its ability to overcome biological barriers and target viral reservoirs. HIV persists in latent reservoirs such as macrophages, lymphoid tissues, and the central nervous system, which are often inaccessible to conventional drugs. Nanoparticles can be designed to cross physiological barriers, including the blood-brain barrier, enabling drug delivery to these hidden sites of infection. Furthermore, surface modification of nanoparticles with ligands or antibodies allows for active targeting of specific cell types, such as CD4+ T cells and macrophages, thereby enhancing treatment specificity.

**Keywords:** Nanoformulated antiretrovirals, nanogels for PrEP , antiretroviral, HIV/AIDS, Targeted drugs. Acquired Immuno-deficiency Syndrome (AIDS),

**INTRODUCTION**

Human Immunodeficiency Virus (HIV) infection and its advanced clinical manifestation,

remain among the most significant global health challenges of the modern era. Since its discovery in the early 1980s, HIV has caused



millions of deaths worldwide and continues to affect millions of individuals across diverse populations. Despite substantial progress in diagnosis, prevention, and treatment, HIV/AIDS persists as a chronic and life-threatening condition, particularly in low- and middle-income countries. <sup>(1-3)</sup>The virus primarily targets the immune system, specifically CD4+ T lymphocytes, leading to progressive immune suppression and increased susceptibility to opportunistic infections, malignancies, and ultimately death if left untreated <sup>(4)</sup>

HIV is a retrovirus belonging to the family Retroviridae and the genus Lentivirus. Its lifecycle is complex and involves multiple stages, including viral entry, reverse transcription, integration into the host genome, replication, assembly, and budding. The virus attaches to host cells via the CD4 receptor and co-receptors such as CCR5 or CXCR4, followed by fusion with the host cell membrane. Once inside the cell, the viral RNA is reverse-transcribed into DNA, which integrates into the host genome, forming a provirus. This integrated viral DNA can remain latent for extended periods, evading immune detection and therapeutic intervention. This latency is one of the key obstacles in achieving a complete cure for HIV infection <sup>(5)</sup>

Over the past few decades, the introduction of antiretroviral therapy (ART), particularly Highly Active Antiretroviral Therapy (HAART), has [www.pharmaerudition.org](http://www.pharmaerudition.org) May 2026, 16(1), 47-58

transformed HIV infection from a fatal disease into a manageable chronic condition. ART involves the combination of multiple drugs that target different stages of the viral lifecycle, including reverse transcriptase inhibitors, protease inhibitors, integrase inhibitors, and entry inhibitors. These therapies effectively suppress viral replication, reduce viral load to undetectable levels, and restore immune function in many patients. Consequently, the life expectancy of individuals living with HIV has improved significantly, and the risk of transmission has been markedly reduced.

However, despite these advancements, conventional HIV treatment strategies are associated with several limitations. One of the most significant challenges is the inability of ART to eradicate the virus completely due to the presence of latent viral reservoirs. These reservoirs are established early during infection and persist in various tissues, including lymphoid organs, the central nervous system, and macrophage-rich compartments. The virus in these reservoirs remains transcriptionally silent and is not affected by antiretroviral drugs, which primarily target actively replicating virus. As a result, interruption of therapy often leads to rapid viral rebound. <sup>(6)</sup>

Another major limitation of conventional therapy is the development of drug resistance. HIV has a high mutation rate due to the error-prone nature of reverse transcriptase, leading to the



emergence of drug-resistant strains. This necessitates the continuous development of new drugs and combination regimens. Additionally, long-term use of ART is associated with various adverse effects, including metabolic disorders, hepatotoxicity, nephrotoxicity, and cardiovascular complications. These side effects can compromise patient adherence, which is critical for maintaining viral suppression and preventing resistance.

Furthermore, many antiretroviral drugs exhibit poor pharmacokinetic properties, such as low solubility, limited bioavailability, and rapid clearance from the body. These factors necessitate frequent dosing, which can be burdensome for patients and further impact adherence. The inability of certain drugs to effectively cross biological barriers, such as the blood-brain barrier, also limits their efficacy in targeting viral reservoirs in the central nervous system. Collectively, these challenges highlight the need for innovative therapeutic strategies that can overcome the limitations of conventional HIV treatment <sup>(7)</sup>

In recent years, nanotechnology has emerged as a promising and innovative approach in the field of biomedical research, offering new possibilities for the diagnosis, prevention, and treatment of various diseases, including HIV/AIDS. Nanotechnology involves the manipulation and application of materials at the

nanoscale, typically ranging from 1 to 100 nanometers. At this scale, materials exhibit unique physical, chemical, and biological properties that can be harnessed for medical applications. These include increased surface area-to-volume ratio, enhanced reactivity, improved solubility, and the ability to interact with biological systems at the molecular level. The application of nanotechnology in medicine, often referred to as nanomedicine, has gained significant attention due to its potential to revolutionize drug delivery systems. Nanocarriers can be engineered to encapsulate therapeutic agents, protect them from degradation, and deliver them to specific target sites within the body. This targeted approach not only enhances the therapeutic efficacy of drugs but also minimizes systemic toxicity and side effects. In the context of HIV/AIDS, nanotechnology offers several advantages over conventional drug delivery methods, including improved pharmacokinetics, controlled drug release, and the ability to target viral reservoirs <sup>(8)</sup>

A wide range of nanocarrier systems have been developed and investigated for HIV treatment. These include liposomes, polymeric nanoparticles, dendrimers, solid lipid nanoparticles, nanomicelles, and inorganic nanoparticles such as gold and silver nanoparticles. Each of these systems has unique properties that make them suitable for



specific applications. For instance, liposomes are biocompatible and can carry both hydrophilic and hydrophobic drugs, while polymeric nanoparticles provide sustained drug release and enhanced stability. Dendrimers, with their highly branched structure, offer high drug-loading capacity and can be functionalized for targeted delivery <sup>(9)</sup>

One of the most significant contributions of nanotechnology to HIV treatment is its ability to target and penetrate viral reservoirs. Nanoparticles can be designed to cross biological barriers, such as the blood-brain barrier, and deliver drugs to otherwise inaccessible sites. Additionally, surface modification of nanoparticles with targeting ligands, antibodies, or peptides enables selective delivery to infected cells, such as CD4+ T cells and macrophages. This targeted approach enhances drug accumulation at the site of infection while reducing off-target effects <sup>(10)</sup>

Nanotechnology also plays a crucial role in improving the pharmacokinetic and pharmacodynamic properties of antiretroviral drugs. By enhancing drug solubility and stability, nanocarriers can increase bioavailability and prolong circulation time in the bloodstream. Controlled and sustained release of drugs from nanoparticles allows for reduced dosing frequency, which can significantly improve patient adherence. The development of long-acting injectable

nanomedicines represents a major advancement in this regard, offering the potential for weekly or monthly dosing instead of daily oral administration <sup>(11)</sup>

In addition to therapeutic applications, nanotechnology is also being explored for HIV prevention and cure strategies. Nanoparticle-based vaccines are being developed to enhance immune responses by improving antigen presentation and stability. Nanotechnology is also facilitating advances in gene therapy, including the delivery of small interfering RNA (siRNA), messenger RNA (mRNA), and gene-editing tools such as CRISPR/Cas systems. These approaches aim to suppress viral replication, eliminate infected cells, or achieve a functional cure by targeting latent reservoirs.

Moreover, nanotechnology-based microbicides and pre-exposure prophylaxis (PrEP) systems are being developed to prevent HIV transmission. These formulations enable localized drug delivery at mucosal surfaces, providing sustained protection against infection. The integration of nanotechnology with other emerging fields, such as artificial intelligence and personalized medicine, further enhances its potential to revolutionize HIV treatment and prevention <sup>(12)</sup>

### **Nanotechnology use in HIV/AIDS Prevention**

Nanotechnology has emerged as a



transformative approach in the treatment of HIV/AIDS, offering innovative solutions to many of the limitations associated with conventional antiretroviral therapy (ART). HIV infection is characterized by persistent viral replication, rapid mutation, and the establishment of latent reservoirs in various tissues, including the central nervous system and lymphoid organs. Although ART has significantly improved the life expectancy of individuals living with HIV by suppressing viral replication, it cannot completely eliminate the virus from the body. Challenges such as poor drug bioavailability, systemic toxicity, drug resistance, and the need for lifelong adherence highlight the necessity for more advanced therapeutic strategies. In this context, nanotechnology provides a promising platform for enhancing drug delivery, improving therapeutic outcomes, and potentially contributing to long-term viral control or eradication<sup>(13)</sup>

Nanotechnology involves the manipulation and application of materials at the nanoscale, typically between 1 and 100 nanometers, where unique physicochemical properties can be utilized for biomedical applications. Nanocarriers are designed to encapsulate antiretroviral drugs and deliver them directly to targeted cells and tissues, thereby improving drug efficacy while minimizing side effects. These nanosystems enhance the solubility and stability of drugs, protect them from premature

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degradation, and allow for controlled and sustained release. As a result, therapeutic drug levels can be maintained for extended periods, reducing the frequency of dosing and improving patient adherence, which is a critical factor in successful HIV treatment<sup>(14)</sup>

A variety of nanocarrier systems have been developed and explored for HIV therapy, each offering distinct advantages. Liposomes, which are phospholipid-based vesicles, are widely used due to their biocompatibility and ability to carry both hydrophilic and hydrophobic drugs. They can fuse with cell membranes, facilitating efficient drug delivery into infected cells. Polymeric nanoparticles, made from biodegradable materials such as polylactic acid and polylactic-co-glycolic acid, provide controlled drug release and improved stability. These nanoparticles are particularly effective in delivering antiretroviral drugs to macrophages, which serve as important reservoirs for HIV. Dendrimers, characterized by their highly branched and well-defined structures, offer high drug-loading capacity and can be functionalized for targeted delivery. Some dendrimers also exhibit intrinsic antiviral activity by interfering with viral entry into host cells. In addition to these systems, solid lipid nanoparticles and nanomicelles are being utilized to enhance the delivery of poorly water-soluble drugs. Solid lipid nanoparticles provide a stable matrix for drug encapsulation and enable controlled



release, while nanomicelles improve drug solubility and facilitate targeted delivery. Metallic nanoparticles, particularly gold nanoparticles, have also gained attention due to their unique properties and ability to inhibit viral entry by interacting with viral proteins. Furthermore, lipid nanoparticles have emerged as a powerful tool for delivering nucleic acid-based therapeutics, such as small interfering RNA (siRNA) and messenger RNA (mRNA), opening new avenues for gene therapy in HIV treatment<sup>(15)</sup>

The effectiveness of nanotechnology in HIV treatment is largely attributed to its advanced mechanisms of drug delivery. Nanoparticles can achieve passive targeting through the enhanced permeability and retention effect, allowing them to accumulate in infected tissues with leaky vasculature. More importantly, active targeting can be achieved by modifying the surface of nanoparticles with ligands, antibodies, or peptides that specifically bind to receptors on HIV-infected cells, such as CD4+ T cells and macrophages. This targeted approach ensures higher drug concentration at the site of infection while reducing systemic exposure and toxicity. Additionally, nanoparticles facilitate cellular uptake through endocytosis, enhancing intracellular drug delivery, which is crucial for inhibiting viral replication<sup>(16)</sup>

One of the most significant advantages of

nanotechnology is its ability to overcome biological barriers, such as the blood-brain barrier, which often limits the effectiveness of conventional drugs. HIV can persist in the central nervous system, forming a reservoir that is difficult to treat with standard therapies. Nanoparticles can be engineered to cross these barriers and deliver drugs directly to these hidden sites, thereby improving the chances of eliminating the virus from all compartments of the body. This capability is particularly important in addressing one of the major obstacles in HIV treatment—the persistence of latent viral reservoirs.

Nanotechnology also plays a crucial role in the development of long-acting antiretroviral formulations. These formulations are designed to release drugs slowly over extended periods, ranging from weeks to months, thereby reducing the need for daily medication. Long-acting injectable nanomedicines have the potential to significantly improve patient adherence, especially in populations where consistent access to healthcare is a challenge. By maintaining stable drug concentrations in the body, these formulations help prevent viral rebound and reduce the risk of drug resistance<sup>(17)</sup>

In addition to improving conventional drug therapy, nanotechnology is enabling the development of novel therapeutic approaches, including gene therapy. Nanocarriers can be used to deliver genetic material such as siRNA,



mRNA, and CRISPR/Cas gene-editing components into target cells. These technologies aim to silence viral genes, inhibit viral replication, or even remove integrated viral DNA from the host genome. Strategies such as “shock and kill,” which involves reactivating latent virus followed by its elimination, and “block and lock,” which aims to permanently suppress viral expression, are being explored with the help of nanotechnology. These approaches hold the potential to achieve a functional cure for HIV <sup>18)</sup>

Furthermore, nanotechnology is contributing to HIV prevention strategies. Nanoparticle-based systems are being developed for pre-exposure prophylaxis (PrEP), enabling sustained release of preventive drugs and reducing the frequency of administration. Nanotechnology is also being used in the development of topical microbicides that can be applied to mucosal surfaces to prevent viral transmission. These formulations provide localized and prolonged protection, enhancing their effectiveness. Additionally, nanoparticle-based vaccines are being investigated to improve antigen delivery and stimulate stronger immune responses, which could lead to the development of an effective HIV vaccine in the future <sup>(19)</sup>

#### **Advantages And Limitations Of Nanotechnology Use In Hiv/Aids Prevention**

Nanotechnology has emerged as a highly promising approach in the management and

treatment of HIV/AIDS, offering innovative solutions to overcome many of the challenges associated with conventional antiretroviral therapy (ART). By utilizing nanoscale materials and delivery systems, researchers have been able to enhance drug efficacy, improve pharmacokinetics, and target viral reservoirs more effectively. However, despite its numerous advantages, nanotechnology also presents several limitations and challenges that must be addressed before it can be fully integrated into routine clinical practice. A balanced understanding of both its benefits and drawbacks is essential for evaluating its role in HIV/AIDS treatment. <sup>(20)</sup>

One of the most significant advantages of nanotechnology in HIV treatment is its ability to enable targeted drug delivery. Conventional antiretroviral drugs are distributed throughout the body, often affecting both infected and healthy cells, which can lead to systemic toxicity and side effects. In contrast, nanocarriers can be engineered to specifically target HIV- infected cells, such as CD4+ T lymphocytes and macrophages, through surface modifications with ligands, antibodies, or peptides. This targeted approach enhances drug concentration at the site of infection while minimizing damage to healthy tissues. As a result, therapeutic efficacy is improved, and adverse effects are significantly reduced. <sup>(21)</sup>



Another major advantage is the improvement in drug bioavailability and solubility. Many antiretroviral drugs have poor water solubility and limited absorption, which reduces their effectiveness. Nanoparticles can encapsulate these drugs, enhancing their solubility and protecting them from enzymatic degradation in the body. This leads to improved absorption and increased bioavailability, allowing for more effective viral suppression. Additionally, nanocarriers can prolong the circulation time of drugs in the bloodstream, ensuring sustained therapeutic levels over extended periods <sup>(22)</sup>

Controlled and sustained drug release is another key benefit of nanotechnology. Traditional ART often requires strict adherence to daily dosing schedules, which can be challenging for patients and may lead to non-compliance. Nanoparticle-based drug delivery systems can be designed to release drugs gradually over time, maintaining consistent drug concentrations in the body. This has led to the development of long-acting formulations that can be administered weekly, monthly, or even less frequently. Such advancements significantly improve patient adherence and reduce the risk of treatment failure due to missed doses <sup>(23)</sup>

Nanotechnology also plays a crucial role in overcoming biological barriers, particularly the blood-brain barrier. HIV can establish reservoirs in the central nervous system, where

conventional drugs have limited access. Nanoparticles, due to their small size and modifiable surface properties, can cross these barriers and deliver drugs directly to these hidden reservoirs. This capability is essential for achieving comprehensive viral suppression and addressing one of the major obstacles in HIV treatment—the persistence of latent virus in inaccessible tissues <sup>(24)</sup>

In addition to targeting physical barriers, nanotechnology enhances intracellular drug delivery. HIV replicates within host cells, making it essential for drugs to reach adequate intracellular concentrations. Nanoparticles facilitate cellular uptake through mechanisms such as endocytosis, allowing drugs to penetrate infected cells more effectively. This results in improved inhibition of viral replication and better overall treatment outcomes. <sup>(25)</sup>

Another advantage of nanotechnology is its potential to reduce drug toxicity and side effects. By delivering drugs specifically to infected cells and tissues, nanocarriers minimize systemic exposure and reduce the likelihood of adverse reactions. This is particularly important in long-term HIV treatment, where patients are required to take medication for life. Reduced toxicity not only improves patient quality of life but also enhances adherence to therapy. Nanotechnology also opens new avenues for innovative therapeutic strategies, including



gene therapy and immunotherapy. Nanocarriers can be used to deliver genetic materials such as small interfering RNA (siRNA), messenger RNA (mRNA), and gene-editing tools like CRISPR/Cas systems. These approaches aim to silence viral genes, inhibit replication, or even remove the integrated viral genome from host cells. Such strategies hold the potential for achieving a functional cure for HIV, which is not possible with conventional ART alone.<sup>(26)</sup>

Another significant limitation is the complexity of nanoparticle design and production. Developing nanocarriers with precise size, shape, surface properties, and drug-loading capacity requires advanced technology and expertise. The manufacturing process is often expensive and time-consuming, which can limit large-scale production and accessibility. This is particularly challenging in low-resource settings, where the burden of HIV/AIDS is highest. Stability is also a major concern in nanotechnology-based drug delivery systems. Nanoparticles may undergo aggregation, degradation, or changes in physicochemical properties during storage or upon exposure to biological environments. These changes can affect their performance, reducing drug efficacy and safety. Ensuring the stability of nanocarriers throughout their shelf life and during administration is a critical challenge that must be addressed<sup>(27)</sup>

Regulatory and approval challenges further complicate the development and commercialization of nanomedicines. Currently, there is a lack of standardized guidelines and regulatory frameworks specifically tailored to nanotechnology-based therapeutics. This creates uncertainty in the approval process and may delay the introduction of new treatments into the market. Additionally, the evaluation of nanomedicines requires specialized testing methods and protocols, which are still being developed. Another limitation is the potential for immune system reactions. The body may recognize nanoparticles as foreign substances, triggering immune responses that can reduce their effectiveness or cause adverse effects. This issue highlights the importance of designing nanocarriers that are not only effective but also immunologically compatible. Ethical and societal concerns also need to be considered. The use of advanced technologies such as gene editing and nanomedicine raises questions about safety, accessibility, and long-term implications. Ensuring equitable access to these advanced treatments is essential to prevent widening disparities in healthcare. Moreover, while many nanotechnology-based approaches have shown promising results in laboratory and preclinical studies, their translation into clinical practice remains limited. Clinical trials are often expensive, time-consuming, and complex, and



there is a need for more robust data to establish the safety and efficacy of these technologies in humans. The gap between research and real-world application remains a significant challenge <sup>(28-29)</sup>

## CONCLUSION

In conclusion, HIV/AIDS continues to pose a significant global health challenge despite decades of advancements in medical science and the widespread use of antiretroviral therapy (ART). While conventional treatment strategies have successfully transformed HIV infection from a fatal disease into a manageable chronic condition, they are still associated with several limitations, including drug resistance, toxicity, poor bioavailability, limited access to viral reservoirs, and the need for lifelong adherence. These challenges highlight the urgent need for more effective and innovative therapeutic approaches. In this context, nanotechnology has emerged as a promising and transformative tool with the potential to revolutionize the prevention, diagnosis, and treatment of HIV/AIDS.

Nanotechnology offers unique advantages due to its ability to manipulate materials at the nanoscale, enabling the development of advanced drug delivery systems known as nanocarriers. These systems, including liposomes, polymeric nanoparticles, dendrimers, and lipid-based nanoparticles, have demonstrated significant potential in

enhancing the delivery and efficacy of antiretroviral drugs. By improving drug solubility, stability, and bioavailability, nanocarriers help maintain optimal therapeutic concentrations in the body while minimizing systemic toxicity. Furthermore, their ability to provide controlled and sustained drug release reduces dosing frequency, thereby improving patient adherence and overall treatment outcomes.

One of the most critical contributions of nanotechnology in HIV treatment is its ability to target viral reservoirs, which remain inaccessible to conventional therapies. The persistence of latent HIV in tissues such as the central nervous system and lymphoid organs represents a major barrier to achieving a complete cure. Nanoparticles can be engineered to cross biological barriers, including the blood-brain barrier, and deliver drugs directly to these hidden sites, thereby enhancing the effectiveness of treatment. Additionally, surface modifications allow for active targeting of infected cells, ensuring precise drug delivery and reducing off-target effects.

Beyond drug delivery, nanotechnology is also paving the way for innovative therapeutic strategies, including gene therapy and immunotherapy. The use of nanocarriers to deliver genetic materials such as siRNA, mRNA, and CRISPR/Cas systems offers new



possibilities for silencing viral genes, inhibiting replication, and potentially eliminating the virus from infected cells. These approaches, along with strategies such as “shock and kill” and “block and lock,” represent important steps toward achieving a functional cure for HIV. Moreover, nanotechnology is playing a significant role in prevention through the development of nanoparticle-based vaccines, microbicides, and pre-exposure prophylaxis systems, which could help reduce the spread of infection.

Despite its immense potential, the application of nanotechnology in HIV/AIDS treatment is not without challenges. Concerns regarding the long-term safety and toxicity of nanomaterials, high production costs, stability issues, and regulatory barriers must be carefully addressed. Additionally, the translation nanotechnology-based therapies from laboratory research to clinical practice remains limited, requiring further investigation and large-scale clinical trials.

Addressing these challenges will require collaborative efforts among researchers, clinicians, regulatory authorities, and policymakers. Overall, nanotechnology represents a groundbreaking advancement in the fight against HIV/AIDS. By overcoming many of the limitations associated with conventional therapies and enabling the development of novel treatment strategies, it

holds the potential to significantly improve patient outcomes and quality of life. Although further research and development are needed, the continued integration of nanotechnology into HIV/AIDS management may ultimately lead to more effective, accessible, and possibly curative solutions, bringing us closer to the goal of ending the global HIV/AIDS epidemic.

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### Conflict of Interest

The authors declare that they have no conflict of interest