Nanotechnology in Stroke Management: From Neuroprotection to Post-Stroke Recovery

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ABSTRACT

Background: *Stroke is a major global health burden, representing one of the leading causes of death and long-term disability. Current therapeutic strategies are limited by narrow treatment windows, poor drug penetration across the blood–brain barrier (BBB), and insufficient support for neuroregeneration.*

Objective: *This review aims to evaluate the role of nanotechnology in stroke management, focusing on its potential in enhancing neuroprotection, promoting post-stroke recovery, and overcoming existing therapeutic limitations.*

Approach: *A comprehensive analysis of recent literature was conducted, emphasizing the application of various nanomaterials—lipid-based, polymeric, metallic, and hybrid nanoparticles—in stroke therapy. Their mechanisms of action, including targeted drug delivery, thrombolysis, BBB penetration, anti-inflammatory effects, and neural repair, are critically reviewed.*

Discussion: *Nanotechnology enables precise, site-specific delivery of therapeutic agents, facilitates real-time imaging, and supports tissue regeneration through multifunctional platforms. Several preclinical studies have demonstrated improved outcomes in stroke models using nanoformulations. Emerging clinical trials further validate their translational potential.*

Conclusion: *Nanotechnology offers a transformative approach in stroke care, addressing both acute intervention and long-term rehabilitation. However, challenges related to safety, scalability, and regulatory approval must be resolved to enable clinical adoption. Future research should focus on multifunctional, biocompatible, and targeted nanoplatforms for integrated stroke management.*

Keywords: *Nanotechnology, Stroke, Ischemic stroke, Nanoparticles, Blood-brain barrier, Neuroprotection, Post-stroke recovery, Drug delivery, Thrombolysis, Neurodegenerations*

1. Introduction

Stroke is a devastating neurological disorder and one of the leading causes of morbidity, mortality, and long-term disability worldwide [1]. It is characterized by a sudden disruption of blood flow to the brain, resulting in oxygen and nutrient deprivation, which rapidly leads to the loss of brain tissue and neurological function. Based on the underlying pathology, stroke can be broadly classified into two major types: ischemic and hemorrhagic. Ischemic stroke, which accounts for approximately 85% of all cases, occurs due to the obstruction of cerebral blood vessels by thrombotic or embolic events. In contrast, hemorrhagic stroke arises from the rupture of blood vessels, leading to bleeding within or around the brain. Regardless of the type, stroke represents a medical emergency requiring prompt diagnosis and intervention to minimize neuronal damage and improve patient outcomes [2]. Currently, the only FDA-approved pharmacological treatment for acute ischemic stroke is intravenous recombinant tissue plasminogen activator (rtPA). Administered within 4.5 hours of symptom onset, rtPA works by dissolving the clot that blocks cerebral blood flow. Despite its proven efficacy, rtPA is associated with several limitations, including a narrow therapeutic time window, low recanalization rates in large vessel occlusions, and a significant risk of hemorrhagic transformation. Furthermore, a large proportion of stroke patients arrive at medical facilities beyond the eligible treatment window, rendering them ineligible for thrombolytic therapy [3]. Mechanical thrombectomy, another established intervention for large vessel occlusions, also has limitations related to accessibility, procedural complexity, and patient eligibility. Beyond acute interventions, the long-term management of stroke remains challenging due to limited strategies for neuroprotection, neuroregeneration, and functional recovery. Secondary injury mechanisms—including oxidative stress, excitotoxicity, inflammation, apoptosis, and disruption of the blood–brain barrier (BBB)—contribute to the expansion of brain damage hours to days after the initial event. Additionally, the BBB poses a significant obstacle to delivering therapeutic agents to the ischemic brain, often resulting in suboptimal drug concentrations and reduced efficacy [4]. In this context, there is a pressing need for innovative therapeutic approaches that can enhance acute neuroprotection, promote vascular repair and neuroplasticity, and support long-term functional recovery.

Nanotechnology has emerged as a powerful interdisciplinary tool with transformative potential in stroke therapy. It involves the manipulation and application of materials at the nanoscale (1–100 nm), offering unique physicochemical properties that are not present in their bulk counterparts. Nanoparticles (NPs) can be engineered to carry drugs, genes, imaging agents, or therapeutic proteins, and can be designed to target specific cells or tissues within the brain [5]. Their ability to cross the BBB, either through passive diffusion or active targeting mechanisms, makes them particularly suitable for central nervous system (CNS) applications [6]. Furthermore, nanocarriers can protect therapeutic agents from degradation, enhance their bioavailability, and enable sustained or stimuli-responsive release, thereby improving the therapeutic index while minimizing systemic toxicity.

Several classes of nanomaterials have been investigated for stroke applications, including lipid-based nanoparticles (liposomes, solid lipid nanoparticles), polymeric nanoparticles (PLGA, chitosan), metal-based nanoparticles (gold, iron oxide), dendrimers, and carbon-based nanostructures (graphene, carbon nanotubes) [7]. These nanocarriers have demonstrated potential in delivering a wide array of therapeutic agents, including thrombolytics, anti-inflammatory drugs, antioxidants, neurotrophic factors, and even stem cells. For example, liposomal formulations of rtPA have been developed to prolong circulation time and reduce off-target effects, while polymeric nanoparticles have been used to deliver neuroprotective peptides directly to ischemic regions.

Moreover, nanotechnology offers opportunities for diagnostic advancements through the development of contrast agents for magnetic resonance imaging (MRI), computed tomography (CT), and near-infrared (NIR) fluorescence imaging, enabling real-time visualization of brain perfusion, inflammation, and BBB integrity. Theranostic nanoparticles, which combine therapeutic and diagnostic functions, represent a particularly promising strategy for personalized stroke management, allowing clinicians to monitor drug delivery and treatment response simultaneously, to acute neuroprotection, nanotechnology holds promise for post-stroke recovery by supporting neural regeneration and functional rehabilitation [8]. Certain nanomaterials have been shown to promote neurogenesis, axonal sprouting, angiogenesis, and synaptic remodeling. Nanofibrous scaffolds, hydrogel systems, and stem cell-loaded nanocarriers are being investigated to restore damaged neural networks and support tissue repair. These approaches aim to enhance the brain's intrinsic capacity for repair, offering hope for long-term functional improvements in stroke survivors, these promising developments, several challenges remain in translating nanotechnology from bench to bedside. Concerns related to nanoparticle toxicity, immunogenicity, biodegradability, and regulatory approval must be thoroughly addressed. Large-scale clinical studies are needed to validate the safety, efficacy, and cost-effectiveness of nano-based therapies in diverse patient populations. Nanotechnology represents a frontier in stroke management, offering innovative solutions to long-standing therapeutic barriers. By enabling targeted delivery, enhanced imaging, and regenerative therapies, nanomedicine has the potential to revolutionize stroke care across the continuum from acute intervention to chronic recovery [9]. Interdisciplinary research and clinical collaboration will be essential to harness its full potential and improve outcomes for stroke patients worldwide.

Table 1: Types of Nanomaterials Used in Stroke Management

Nanomaterial Type	Composition	Advantages	Application in Stroke
Lipid-based NPs	Liposomes, Solid Lipid Nanoparticles	Biocompatible, crosses the BBB, controlled release	Delivery of anti-inflammatory and thrombolytic agents
Polymeric NPs	PLGA, PEG, chitosan	Biodegradable, modifiable surface, sustained release	Neuroprotective drug delivery, siRNA delivery
Metal-based NPs	Gold, Silver, Iron oxide	Imaging contrast agents, magnetic targeting	MRI imaging, ROS scavenging, targeted delivery
Carbon-based NPs	Carbon nanotubes, graphene oxide	High surface area, conductivity	Neuroregeneration scaffolds, drug carriers
Hybrid NPs	Combinations of polymer/lipid/metal	Multifunctional, synergistic effects	Theranostic applications, drug delivery + imaging

Table 2: Mechanisms of Nanotechnology in Stroke Therapy

Mechanism	Description	Nanotechnology Role
Blood-Brain Barrier (BBB) Penetration	NPs enable drug passage across the BBB without disruption	Surface modifications (PEGylation, ligands) facilitate BBB crossing
Thrombolysis	Rapid dissolution of clots to restore cerebral blood flow	Targeted delivery of rtPA, magnetic targeting for clot resolution
Anti-inflammatory Action	Reduction of neuroinflammation and cytokine storm post-stroke	NPs delivering corticosteroids, NSAIDs, or siRNA
Oxidative Stress Mitigation	Neutralizing ROS to prevent neuronal death	Antioxidant-loaded NPs (e.g., cerium oxide, gold NPs)
Neuroregeneration	Promoting angiogenesis, synaptic repair, and neuronal survival	NPs delivering growth factors (BDNF, VEGF), stem cell carriers
Imaging and Diagnosis	Early detection and monitoring of stroke lesion evolution	MRI, PET contrast agents, fluorescent quantum dots

Table 3: Preclinical and Clinical Advancements in Nanomedicine for Stroke

Nanomaterial Used	Target Outcome	Results	Stage
PEG-PLGA nanoparticles	Anti-inflammatory delivery	↓ infarct size, ↑ neuronal survival	Preclinical (rat)
Liposome-rtPA conjugate	Targeted thrombolysis	Enhanced clot resolution, less hemorrhage	Preclinical
Iron oxide nanoparticles	Stroke lesion imaging (MRI)	Improved lesion visualization	Clinical Phase I
Cerium oxide nanoparticles	ROS scavenging, neuroprotection	↓ oxidative stress, ↑ cognitive recovery	Preclinical
Chitosan nanoparticles	VEGF delivery for neuroregeneration	↑ angiogenesis, improved motor function	Preclinical

2. Role of Nanotechnology in Acute Stroke Management

Acute stroke management focuses on the timely restoration of cerebral blood flow and the reduction of secondary injury mechanisms such as inflammation, oxidative stress, and excitotoxicity. Traditional pharmacological interventions are hampered by limitations such as poor blood–brain barrier (BBB) permeability, rapid systemic clearance, and dose-limiting toxicity [10]. Nanotechnology offers a sophisticated platform for overcoming these challenges by enabling site-specific delivery of therapeutics, prolonged drug circulation, and controlled release. This section explores the major contributions of nanotechnology in acute stroke care.

2.1 Targeted Thrombolysis

Intravenous administration of recombinant tissue plasminogen activator (rtPA) remains the standard therapy for acute ischemic stroke. However, its use is constrained by a narrow therapeutic window (4.5 hours), risk of hemorrhagic complications, and systemic side effects. Nanocarriers provide a promising strategy to enhance the efficacy and safety of thrombolytic therapy [11]. Nanoparticles such as liposomes, polymeric micelles, and magnetic nanoparticles have been used to encapsulate thrombolytics, protecting them from premature degradation and facilitating targeted delivery to thrombotic sites. For instance, magnetic nanoparticles functionalized with rtPA can be directed toward the clot using an external magnetic field. Once localized, these carriers can release the drug directly at the occlusion site, significantly improving clot dissolution while minimizing off-target effects and systemic bleeding risk. *Stimuli*-responsive nanocarriers have been developed to release thrombolytics only under specific conditions, such as acidic pH or elevated enzymatic activity within the ischemic microenvironment. These approaches aim to enhance local drug bioavailability while reducing the systemic exposure associated with conventional administration.

2.2 Blood–Brain Barrier (BBB) Penetration

The BBB is a highly selective barrier that restricts the entry of most therapeutic agents into the brain parenchyma. This presents a significant obstacle for delivering neuroprotective drugs to ischemic regions following stroke. Nanotechnology offers multiple strategies to traverse or bypass the BBB effectively [12]. Surface-modified nanoparticles can exploit receptor-mediated transcytosis to cross the BBB. Ligands such as transferrin, lactoferrin, and apolipoprotein E have been used to decorate nanoparticle surfaces, enabling their recognition and transport by endothelial cell receptors. For example, liposomes conjugated with transferrin have shown increased uptake into the brain and improved delivery of neuroprotectants. Nanocarriers can transiently open tight junctions between endothelial cells or be engineered to respond to external stimuli (e.g., ultrasound, magnetic fields) that enhance BBB permeability [13]. Once inside the brain, these carriers can release drugs in a controlled manner, ensuring high local concentrations and improved therapeutic outcomes.

2.3 Anti-Inflammatory and Antioxidant Delivery

Ischemic stroke triggers a cascade of secondary injury mechanisms, including oxidative stress, activation of microglia, and release of pro-inflammatory cytokines. These processes exacerbate neuronal death and expand the infarct area. Delivering anti-inflammatory and antioxidant agents in the acute phase can mitigate these effects and preserve neuronal function [14].

Nanocarriers have been employed to deliver bioactive compounds with anti-inflammatory and antioxidant properties. For example:

- Polymeric nanoparticles loaded with curcumin or resveratrol have shown the ability to cross the BBB and inhibit the activation of microglia and NF-κB signaling pathways, thereby reducing neuroinflammation.
- Cerium oxide nanoparticles (nanoceria) act as potent reactive oxygen species (ROS) scavengers. Due to their regenerative redox cycling between Ce^{3+} and Ce^{4+} states, they provide sustained antioxidant activity, protecting neurons from oxidative damage.

These nanoformulations not only enhance the bioavailability and brain-targeting efficiency of the drugs but also reduce the frequency and dosage required, lowering the risk of systemic toxicity.
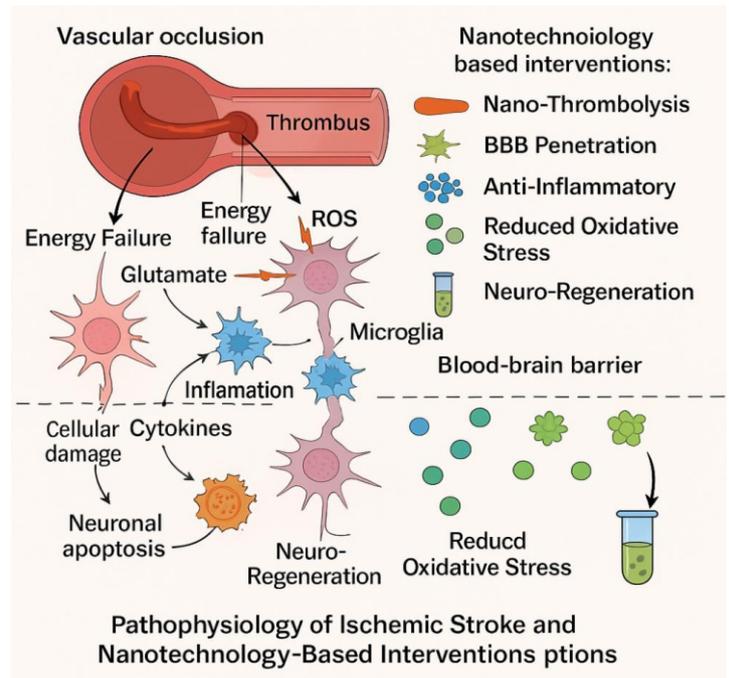
This infographic illustrates the multi-phase pathophysiology of stroke, including vascular occlusion, excitotoxicity, oxidative stress, inflammation, and neuronal death. It also highlights how various nanotechnology-based interventions target different stages of this cascade. Lipid-based nanoparticles and polymeric carriers are shown to enhance blood–brain barrier penetration for targeted drug delivery. Metal-based nanoparticles illustrate roles in reactive oxygen species (ROS) scavenging and neuroimaging. Additionally, hybrid nanoparticles demonstrate applications in thrombolysis, inflammation modulation, and neural regeneration. The figure emphasizes the potential of nanomedicine to address both acute neuroprotection and post-stroke recovery, supporting a paradigm shift in stroke therapy through precision medicine.

3. Nanotechnology in Neuroprotection

Neuroprotection refers to strategies aimed at preserving the structure and function of neurons following a stroke. The goal is to limit neuronal death in the ischemic core and penumbra, prevent the spread of secondary injury, and support long-term neurological function [14-15].

Traditional neuroprotective approaches have largely failed in clinical trials due to poor brain penetration, systemic toxicity, and inadequate targeting.

Nanotechnology provides a versatile platform to overcome these limitations, enabling the precise delivery of neuroprotective agents to ischemic regions with improved pharmacokinetic profiles. This section highlights two key areas where nanotechnology contributes significantly to neuroprotection: mitochondrial preservation and stem cell-nanoparticle synergy.

3.1 Mitochondrial Protection

Mitochondria play a central role in stroke pathology by regulating energy metabolism, calcium homeostasis, and the generation of reactive oxygen species (ROS). During ischemia and reperfusion, mitochondrial dysfunction leads to excessive ROS production, ATP depletion, and the initiation of apoptotic pathways, ultimately resulting in neuronal death. Therefore, strategies that protect mitochondrial integrity are crucial for limiting ischemic damage [16]. Nanocarriers can be engineered to deliver mitochondria-targeted therapeutics directly to neurons. For instance, nanoparticles loaded with coenzyme Q10, a key component of the mitochondrial electron transport chain, have been shown to restore mitochondrial function and reduce oxidative stress in experimental stroke models. Similarly, mitochondria-targeted antioxidants, such as MitoQ (a triphenylphosphonium-conjugated ubiquinone), encapsulated within liposomes or polymeric nanoparticles, effectively localize to the mitochondrial membrane, where they neutralize ROS and prevent mitochondrial permeability transition [17]. Peptide-functionalized nanoparticles have been developed to recognize mitochondrial surface markers, enhancing targeting specificity. These systems not only preserve mitochondrial structure and function but also reduce apoptosis, stabilize membrane potential, and support neuronal survival in the ischemic penumbra—the area of partially viable tissue surrounding the infarct core.

3.2 Stem Cell–Nanoparticle Synergy

Stem cell therapy holds promise for stroke recovery due to its potential to replace lost neurons, modulate inflammation, and promote endogenous repair mechanisms. However, the clinical application of stem cells is hampered by low cell survival, poor engraftment, and limited homing to the injury site. Nanotechnology offers several solutions to enhance the therapeutic efficacy of stem cells in the ischemic brain [18]. Magnetic nanoparticles (MNPs) are commonly used to label stem cells, allowing them to be guided magnetically to the lesion site after systemic or intracerebral administration. This approach improves the localization and retention of stem cells in the ischemic region, thereby enhancing their therapeutic potential. MNPs also enable non-invasive tracking of transplanted cells using magnetic resonance imaging (MRI), facilitating real-time monitoring of cell migration and distribution. In addition to tracking and guidance, nanoscale scaffolds and hydrogel matrices provide a supportive microenvironment for transplanted cells. These biomimetic materials mimic the extracellular matrix, promoting cell adhesion, proliferation, and differentiation. For example, nanofiber-based scaffolds made from materials like polycaprolactone (PCL) or chitosan have been used to deliver neural stem cells to the stroke-affected brain, resulting in improved tissue integration and neurogenesis, nanoparticle-mediated gene or drug delivery to stem cells can precondition them for better survival and function in the hostile post-stroke environment [19].

For instance, loading stem cells with anti-apoptotic or angiogenic factors via nanoparticle vectors can enhance their resistance to ischemic stress and promote vascular remodeling, The combination of nanotechnology with stem cell therapy addresses several bottlenecks in regenerative stroke treatment. By improving targeting, enhancing survival, and enabling functional integration, nanotechnology significantly amplifies the reparative potential of cell-based therapies in stroke.
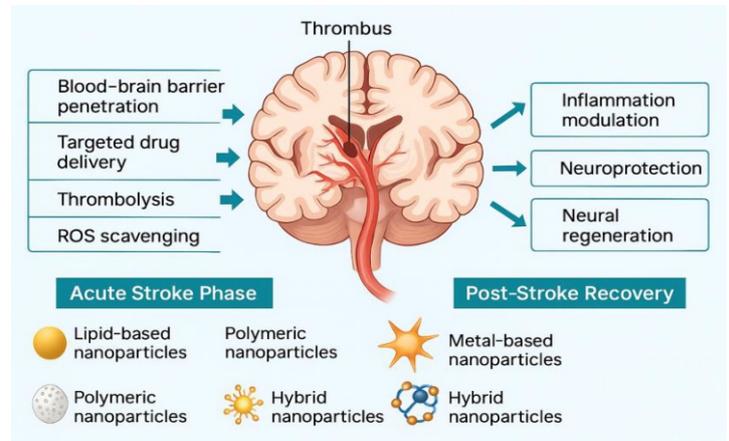

Figure 2. Schematic representation of nanotechnology applications in stroke therapy.

This figure illustrates the integration of nanomaterials into various stages of stroke management. Key applications include nanoparticle-mediated thrombolysis, blood–brain barrier (BBB) penetration, anti-inflammatory delivery, neuroprotective strategies, and neural regeneration. Nanocarriers such as lipid-based, polymeric, and metal-based nanoparticles are shown delivering drugs or genes to specific brain regions affected by ischemia, supporting both acute neuroprotection and long-term recovery. The image also highlights nano-enabled imaging tools that assist in stroke diagnosis and therapeutic monitoring.

4. Nanotechnology in Post-Stroke Recovery

Beyond acute intervention and neuroprotection, nanotechnology plays a pivotal role in promoting long-term recovery following stroke. Post-stroke recovery involves complex processes such as neuroregeneration, angiogenesis, synaptic remodeling, and functional reorganization of the brain. Conventional therapies are often insufficient to support these multifactorial regenerative events. Nanomaterials provide unique advantages in enhancing cellular repair, guiding tissue regrowth, and enabling precise monitoring of recovery [20]. This section highlights key nanotechnology-driven strategies that contribute to post-stroke rehabilitation and regeneration.

4.1 Neuroregeneration and Angiogenesis

Restoring lost neuronal connections and vascular networks is critical for functional recovery after stroke. Nanotechnology facilitates this process by providing biocompatible scaffolds and controlled release systems for regenerative biomolecules [21]. Hydrogels, nanofibers, and self-assembling peptide-based nanomaterials serve as three-dimensional scaffolds that mimic the extracellular matrix (ECM), offering structural support for axonal regrowth and cellular migration. These scaffolds can be functionalized with cell-adhesion peptides and neurotrophic factors to enhance their bioactivity. For example, nanofibrous scaffolds loaded with brain-derived neurotrophic factor (BDNF) promote neurite outgrowth and synaptic plasticity in damaged brain tissue.

Vascular endothelial growth factor (VEGF) and other angiogenic

agents can be encapsulated within nanoparticles or embedded in nanoscaffolds for sustained release, stimulating angiogenesis in the ischemic brain. Revascularization not only improves nutrient and oxygen supply to the infarcted area but also creates a favorable microenvironment for neuronal survival and repair. The integration of nanoengineered biomaterials with mesenchymal stem cells (MSCs) or neural progenitor cells further enhances the regenerative effect, resulting in improved functional outcomes in preclinical models.

4.2 Imaging and Monitoring

Effective post-stroke management requires precise monitoring of lesion evolution, therapeutic response, and neuroplastic changes. Nanotechnology has revolutionized neuroimaging by providing contrast-enhancing agents with superior resolution and specificity [22]. Quantum dots, gold nanoparticles, and superparamagnetic iron oxide nanoparticles (SPIONs) have been employed as contrast agents in magnetic resonance imaging (MRI), positron emission tomography (PET), and computed tomography (CT). These nanoparticles improve visualization of ischemic lesions, track stem cell migration, and monitor the biodistribution of therapeutic agents. For instance, SPION-labeled stem cells can be non-invasively tracked in vivo using MRI, providing valuable insights into cell survival, localization, and therapeutic engagement. Theranostic nanoparticles integrate both diagnostic and therapeutic functions, enabling simultaneous imaging and drug delivery. Such dual-function platforms represent a major step toward personalized stroke treatment and real-time treatment optimization.

4.3 Functional Rehabilitation

Recovery of motor and cognitive function post-stroke often requires intensive rehabilitation. Nanotechnology is contributing to this domain through the development of stimuli-responsive nanomaterials capable of modulating neural activity and enhancing neuroplasticity. Smart nanomaterials, such as those responsive to light (photothermal), magnetic fields (magnetothermal), or electrical stimuli, are being investigated for neurostimulation and neuromodulation applications. For example, magnetic nanoparticles embedded in wearable devices or injectable matrices can be activated by external magnetic fields to stimulate neural circuits involved in motor control, thereby accelerating motor recovery. Similarly, optogenetic nanoparticles can deliver gene constructs that sensitize neurons to light, enabling precise control of neuronal firing patterns [23. These innovative approaches aim to augment conventional rehabilitation therapies, promoting rewiring of neural networks and enhancing cognitive and physical recovery in the chronic phase of stroke.

5. Recent Advances and Clinical Trials

While nanotechnology holds immense promise for stroke management, its clinical translation is still in early stages. However, several nanomedicine strategies have entered preclinical and early-phase clinical evaluation, offering hope for next-generation stroke therapeutics.

- **Liposomal rtPA formulations:** These aim to enhance thrombus specificity and reduce hemorrhagic complications by encapsulating rtPA in liposomes or polymeric nanoparticles. Clinical studies are ongoing to assess their efficacy and safety compared to standard thrombolysis.
- **Exosome-based nanocarriers:** Derived from stem cells or immune cells, exosomes serve as natural nanoscale delivery vehicles. Early research indicates their ability to cross the BBB, carry neuroprotective molecules (e.g., miRNAs, proteins), and promote neurogenesis and angiogenesis. Phase I trials are being initiated to test their safety in stroke patients.
- **Nanoparticle-mediated gene therapy:** DNA- and RNA-loaded nanoparticles are being explored for modulating post-stroke inflammation, promoting neurotrophic signaling, and reprogramming glial cells into neurons. While most studies are in animal models, the results are promising for future translation.

Despite these encouraging developments, several challenges must be addressed:

- Long-term safety and biodegradability of nanomaterials remain under scrutiny.
- Immune responses, particularly to foreign or synthetic nanoparticles, may limit repeat dosing.
- Scalability and reproducibility in nanoparticle synthesis need optimization for clinical manufacturing.
- Regulatory approval pathways for nano-based stroke therapies require clearer guidance and standardization.

Nonetheless, interdisciplinary collaboration among material scientists, neurologists, and regulatory bodies is gradually bridging the gap between bench and bedside [24-26].

6. Challenges

Despite the promising advancements in nanotechnology for stroke diagnosis, treatment, and rehabilitation, several challenges hinder its widespread clinical application. Bridging the gap between experimental success and real-world implementation requires addressing key technical, biological, and regulatory barriers.

6.1 Toxicity and Clearance

One of the major concerns associated with nanomaterials is their potential toxicity and long-term accumulation in biological systems. Many inorganic nanoparticles, such as gold, silver, and quantum dots, exhibit limited biodegradability and may persist in tissues, leading to chronic inflammation or organ dysfunction. Moreover, the size, shape, surface charge, and composition of nanoparticles significantly influence their interaction with biological systems, affecting biodistribution, cellular uptake, and immune responses. To mitigate these risks, current research is focused on developing biodegradable and biocompatible nanoparticles, such as those made from lipids, polysaccharides (e.g., chitosan), or FDA-approved polymers (e.g., PLGA). These materials are more likely to be metabolized or excreted safely, reducing the risk of toxicity. Comprehensive in vivo toxicological studies, including long-term follow-up, are essential to ensure the safety of nanomedicine candidates.

6.2 Scale-Up and Manufacturing

The scalable and reproducible production of nanoparticles with consistent quality is another critical challenge. Laboratory-scale synthesis often involves complex procedures that may not translate efficiently to industrial-scale manufacturing. Parameters such as particle size distribution, surface functionalization, drug loading efficiency, and sterility must be tightly controlled to ensure batch-to-batch consistency and clinical reliability. Efforts are underway to standardize nanoparticle production using automated microfluidic systems and continuous-flow reactors, which offer better control over physicochemical parameters. The cost-effective and environmentally sustainable manufacturing techniques are being explored to support large-scale deployment.

6.3 Regulatory and Ethical Considerations

The regulatory landscape for nanomedicine remains underdeveloped compared to conventional pharmaceuticals. Regulatory agencies such as the FDA and EMA currently lack standardized guidelines for assessing the safety, pharmacokinetics, and efficacy of nanotherapeutics, particularly those involving multifunctional or hybrid systems [23-26]. Establishing clear protocols for preclinical evaluation, including biodistribution studies, immunotoxicity, and long-term safety assessments, is vital. In parallel, ethical considerations such as patient consent, data privacy in theranostic applications, and equitable access to advanced nanotechnologies must be addressed to ensure responsible innovation.

7. Conclusion

Nanotechnology has emerged as a transformative approach in the comprehensive management of stroke, offering innovative solutions across the continuum of care—from acute thrombolysis and neuroprotection to long-term neuroregeneration and functional recovery. By enabling precise targeting, enhanced blood–brain barrier penetration, controlled drug release, and advanced imaging capabilities, nanomedicine addresses many limitations of conventional stroke therapies. Various nanomaterials—lipid-based, polymeric, inorganic, and hybrid platforms—have shown promise in improving drug efficacy, minimizing systemic toxicity, and supporting neural repair. Moreover, nanotechnology-based tools are reshaping stroke rehabilitation through neurostimulation, smart delivery systems, and real-time monitoring via theranostic platforms. These advancements and challenges, such as biocompatibility, scalability, regulatory hurdles, and long-term safety, remain. Future progress depends on robust interdisciplinary collaboration among neuroscientists, clinicians, nanotechnologists, and regulatory bodies. With continued innovation and translational efforts, nanotechnology holds the potential to significantly improve stroke outcomes and establish a new standard of personalized, precision-driven cerebrovascular care.

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