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ARTIFICAL INTELLIGENCE AND NANOTECHNOLOGY IN MIGRAINE DRUG DELIVERY TRENDS

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Abstract:

Migraine is a common disabling neurological disorder for which rapid and effective drug delivery is a major therapeutic challenge. Conventional oral administration of antimigraine drug may lead to delayed absorption, gastrointestinal disturbances, first pass metabolism, low bioavailability and difficulty in achieving effective concentration of drug in the brain. Recent advances in nanotechnology have led to the emergence of novel drug-delivery systems such as nanoemulsions, liposomes, polymeric nanoparticles, solid lipid nanoparticles, nanostructured lipid carriers, micelles and nanogels that can improve drug solubility, stability, bioavailability, controlled release and brain targeting. Intranasal nose-to-brain delivery, in particular, has received considerable attention due to its ability to harness olfactory and trigeminal pathways, enabling direct delivery toward the brain, bypassing the blood–brain barrier and first-pass metabolism.Nanotechnology, artificial intelligence (AI) and machine learning (ML) are emerging as powerful tools for prediction and optimisation of drug-delivery systems. Artificial intelligence can be used for formulation design, selection of nanocarrier components, prediction of drug-excipient interactions, optimisation of critical parameters of formulations, pharmacokinetic prediction and development of personalised treatment strategies. Recent studies show that the combination of AI and nanotechnology can speed up the development of smart, targeted and patient-specific drug-delivery systems. However, important considerations include challenges such as mucociliary clearance, formulation stability, nanoparticle safety, scalability, regulatory requirements and limited clinical translation. The review highlights recent developments in AI-assisted nanotechnology for migraine drug delivery, with special emphasis on nose-to-brain systems, nanocarriers, formulation optimisation, personalised therapy, current challenges and future prospects.

Key Word: *Migraine; Artificial Intelligence; Machine Learning; Nanotechnology; Nanoparticles; Nanoemulsion; Liposomes; Nose-to-Brain Delivery; Drug Delivery; Personalized Medicine*

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INTRODUCTION:

Migraine is a common and important primary headache disorder characterised by recurrent attacks of moderate to severe headache, often unilateral (Ruschel & Jesus, 2024). These headaches are marked by throbbing pain that gets worse with physical activity and is often accompanied by symptoms such as nausea, vomiting, a sensitivity to light (photophobia), and sound (phonophobia) (Unal-Cevik & Arslan, 2023).

Migraine is a common and important primary headache disorder characterised by recurrent attacks of moderate to severe headache, often unilateral (Mungoven et al., 2021). These headaches are associated with a throbbing pain that worsens with physical activity and is often accompanied by symptoms such as nausea, vomiting, and sensitivity to light (photophobia) and sound (phonophobia).

Artificial intelligence driven diagnosis provides a possible way to deal with diseases especially in places with limited collaborative healthcare. Moreover, digital health tools are addressing the continuous shortage of physicians with computer-assisted and computer-based diagnostic solutions (Fahim et al., 2025). They also make large-scale population studies and clinical trials more efficient.To evaluate machine learning applications in migraine research, specific methodological frameworks should be adopted, such as homogeneity of groups based on clinical phenotype, appropriate sample size calculation, quality control of preprocessing data, transparent model evaluation, interpretability of results, and open data sharing (Yella et al., 2025). The understanding of migraine pathophysiology, particularly the role of key mediators like CGRP, which shows increased levels in plasma, saliva, tears, and cerebrospinal fluid of migraine patients, is essential to develop effective AI-based diagnostic and therapeutic approaches (Tanaka et al., 2024).

Overview of Migraine

Most doctors will categorise migraine headaches into three types: without aura, with aura, and chronic. Migraine without aura is the most common. It is characterised by throbbing, usually one-sided pain lasting four to seventy-two hours, often with nausea and vomiting. It's a big reason that nasal and other nanocarrier-based options have drawn so much research interest. Vomiting matters a lot for drug delivery: a patient who cannot keep a pill down requires another route altogether(Khan et al., 2021).

Migraine with aura has a warning phase, usually visual disturbances like flashing lights or blind spots, sometimes numbness or difficulty speaking, which develops over five to twenty minutes before the headache begins (van Dongen & Haan, 2019).

TYPE OF MIGRINE

1. Aura-free migraine:

This kind of migraine is the most common. It often alters one side of the head and is defined by a throbbing or pulsating headache. Routine phisical activity may exacerbate the pain, which may also be accompanied by nausea, vomiting, photophobia, or phonophobia. If left untreated, attacks can persist anywhere from a few hours to many days . (Goadsby et al., 2017)

2. Aura-producing migraine:

This kind is defined by neurological symptoms called an aura that might appear before to or during the headache. Zigzag lines, flashing lights, and transient blind patches are examples of common visual disturbances. Also, some people may feel numbness, tingling, or have trouble speaking. In most trigger, the aura is transient and occurs gradually . (*Migraine Visual Aura & Other Visual Phenomena*, n.d.)

3. Long standing migraine:

Chronic migraine is defined as headaches on 15 or more days per month for >3 months with migraine features on ≥8 mornings per month. Chronic migraine can have a significant impact on daily activities, such as work, schoolwork and quality of life (*Chronic Migraine Pathophysiology and Treatment: A Review of Current Perspectives - PMC*, n.d.).

It is important to recognise these migraine variants for the development of effective treatment approaches and advanced drug delivery approaches (*Migraine Variants Treatment & Management*, 2026).

Pathophysiology of Migraine:

Trigeminovascular Activation, CGRP Signaling, Neurogenic Inflammation, and Sensitization

1.Trigeminovascular activation

The trigeminovascular system is made up of trigeminal nerve fibers that supply the dura mater and the intracranial blood vessels (Terrier et al., 2021). Activation of these afferent fibers transmits nociceptive information to the trigeminal ganglion and the trigeminal nucleus caudalis, from which it is transmitted to higher brain centers for processing(Yella et al., 2025) .

2. CGRP signaling

CGRP is an important neuropeptide released from activated trigeminal nerve terminals. It binds to receptor CGRP and induces vasodilation, neuron excitation and neuron sensitization. CGRP may also have local activity within the trigeminal ganglion and central trigeminal pathways, contributing to the amplification of migraine pain (C.-L. Lu et al., 2026).

3.Neurogenic inflammatory

Activation of trigeminal afferent fibers can lead to the release of CGRP and other neuropeptides such as substance P. These neuropeptides act on vascular and immune cells including mast cells to induce vasodilation and release of pro-inflammatory mediator (Christensen et al., 2025). This process is commonly known as neurogenic inflammation. However, the role of classical dural inflammation in migraine pathophysiology is controversial.

Current therapy:

NSAIDs, triptans, CGRP-targeted therapies and preventive medicines.

The existing therapy for migraine encompasses the treatment of prolonged migraine attacks by acute forms of therapy and preventions of frequent and severe migraine attacks by prophylactic drugs (D'Amico & Tepper, 2008). The non-steroidal anti-inflammatory drugs (NSAIDs), such as ibuprofen, naproxen, and diclofenac, are recommended for mild-to-moderate migraine attacks due to their ability to inhibit cyclooxygenase, thus reducing the level of prostaglandin (Pardutz & Schoenen, 2010). The drugs that are considered migraine-specific are serotonin receptor agonists, including sumatriptan, rizatriptan, and zolmitriptan, which target 5-HT_1B/5-HT_1D receptors and decrease trigeminal neurotransmission. Recently, new classes of drugs for migraine treatment have been developed, such as calcitonin gene-related peptide (CGRP) antagonistsl .

Limitations of Conventional Migraine Drug Delivery

Migraine drugs have traditionally been administered in several ways, such as by mouth, in capsules, by injection, etc. These methods have a number of limitations. First, oral absorption of oral dosage forms is poor with variable peak plasma concentration and slow onset of action. Migraine causes intermittent malfunction of the stomach or intestines hence making oral administration of migraine drugs inappropriate (Esim et al., 2021). Secondly, most of the migraine patients usually have nausea or vomiting which makes it difficult to administer the drugs properly. Some migraine medications also have a short duration of action and may need to be given frequently to treat the condition. This could lead to drug overuse and abuse(*Migraine Treatment*, n.d.).

Moreover, traditional drug delivery system for migraine has been linked with reduced brain targeting. This is mainly because of the blood-brain barrier which stops most of the drugs from entering and targeting the brain (Niazi, 2023). Some drugs are good for controlling migraine but cannot be used because they can't get into the brain. Thus, BBB is a major barrier for the delivery of migraine drugs. Most migraine medications currently available are ineffective and cause side effects such as heart problems, sleepiness, fatigue, dizziness and digestive problems (Niazi, 2023).

Most researchers are now involved in developing sophisticated delivery systems for brain-targeted drugs for effective migraine management. Some of the promising modern delivery systems for migraine management are nano-based carriers, nasal delivery and smart drugs (*Nose-to-Brain Delivery for Migraine*, n.d.). These novel delivery systems are promising, efficient and safe. Meanwhile, personalised drugs that can foresee and meet patient-specific needs have been regarded as an effective strategy for migraine management.foresee and meet patient-specific needs have been regarded as an effective strategy for migraine management (Paul G. Mathew, n.d.).

Drug Class	Representative Drugs	Route of Administration	Mechanism of Action	Major Delivery Limitations
Analgesics	Paracetamol, Aspirin .	Oral	Pain relief through inhibition of prostaglanding synthesis.	Delayed onset , gastrointestinal irritation , variable absorption during migraine attacks
Nonsteroidal Antinflammtory drug [NSAIDs]	Ibuprofen, Naproxen, Diclofenac.	Oral , Injection	Inhibit cyclooxygenase enzyme and reduce inflammation	Gastric toxicity , poor patient compliance with repeated dosing limitaed brain targeting
Triptans	Sumatriptan, Rizatriptan .	Oral , Nasal	5-HT / 1D receptor agonist causing cranial vasoconstriction and inhibion of neuropeptide release	Low Oral bioavailability, extensive first pass metabolism, cardiovascular adverse effects, frequent dosing
Ergot Alkaloids	Ergotamines .	Oral nasal	Vasoconstrution and modulation of serotonergic receptor	Poor and unpredictable absorption systemic toxicity , nassea and vomiting
CGRP Receptor antagonists	Ubrogepant Rimegepant Atogepant	Oral	Block calcitonin generelated[CGRP] Signaling	Limited brain delivery,dependence on systemic circulation,potential lvariablity in patient response

Table:.1 Conventional Migraine Drug And Their Delivery Limitations

Nanotechnology in Migrine Drug Delivery

Paper on Nanotechnology in Migraine Drugs Nanotechnology is a new concept and has a bright future for applications in medicine including migraine drug delivery (Gowtham et al., 2023). Nanotechnology can be utilized to enhance the water solubility, stability, absorption, bioavailability and controlled release of drugs. Migraine drugs can have several adverse side effects, including low water solubility, poor absorption, gastrointestinal irritation, and slow onset of action (Cahyani et al., n.d.-a). Scientists are trying to improve the current state of pharmaceutical delivery systems by using various methods and make the treatment safer and more effective. There are different types of colloidal drug delivery system used in medicine and also use for research purpose (Cahyani et al., n.d.-b). These systems are liposomes, polymeric nanoparticles, solid lipid nanoparticles, nanostructured lipid carriers and nanoemulsions (H. Lu et al., 2021).

they can be used to encapsulate or adsorb the drug and help it reach the target site while protecting the substance inside them (Islam, 2025). The colloidal carrier systems can increase the apparent solubility of drugs that are not easily absorbed and thereby increase their effectiveness due to the prolonged release of the active substance (Liu et al., 2024) . Another advantage of colloidal carriers is that they can deliver the substance directly to the target site. Systems to deliver drugs across the blood-brain barrier to the central nervous system are under development by researchers (Jiao et al., 2024). Targeting may significantly improve therapeutic efficacy and minimize systemic toxicity by allowing drug delivery to the desired tissue or cell. “Intranasal nanotechnology is a promising way to deliver various substances, including drugs (Yetisgin et al., 2020).

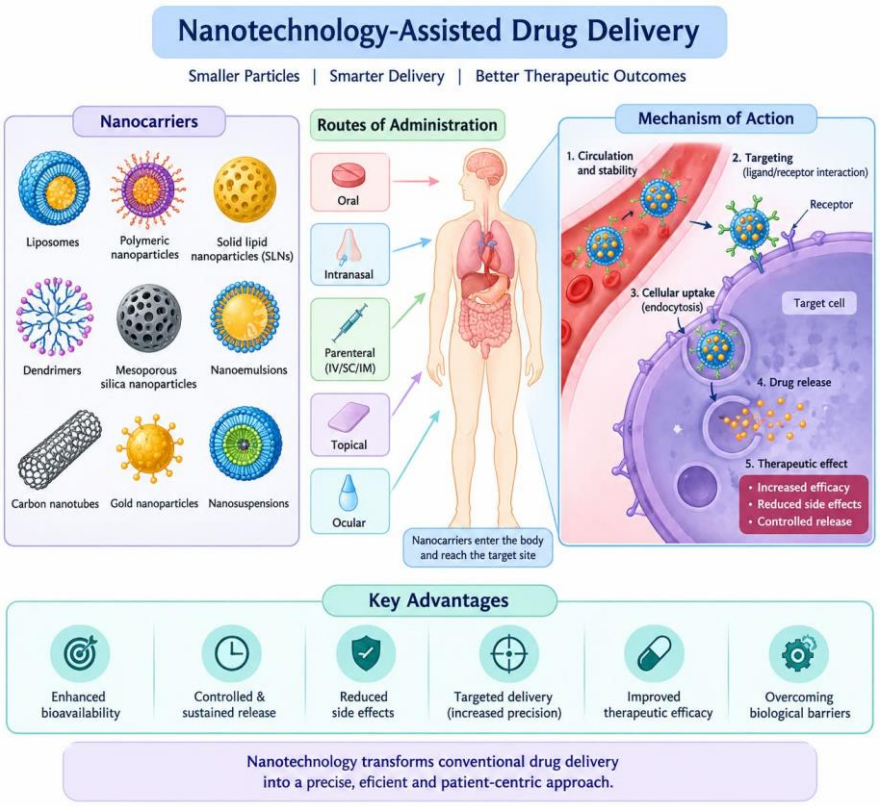

Figure-1: Nanotechnology-Assisted Drug Delivery

The nasal route is an alternative to the traditional routes of drug administration. The nasal cavity provides a simple route to the central nervous system (Alwali et al., 2026a). For this reason, nano carriers are under development to exploit this anatomical location to obtain better results than traditional methods. Intranasal delivery of drug particles has been previously demonstrated as a route to bypass the blood-brain barrier and reach the target cells (Koo et al., 2024). Nanotechnology can also help to improve the stability of the drug inside and outside the body. However, despite all the benefits, practical applications of nanotechnology carriers may be limited due to possible problems with nanoparticle toxicity and stability, complicated production methods, financial limitations and regulatory barriers (Yusuf et al., 2023). Moreover, there is a lack of complete understanding of the pharmacokinetics of various nanocarriers,and clinical trials are necessary to confirm the benefits of employing such devices for treating migraines (Alshawwa et al., 2022).

As a result, several features of nanotechnology have the potential to enhance drug delivery systems and, consequently, improve disease treatment. Even while preclinical evidence appears encouraging, further study is required to completely comprehend how these systems impact the human body and any potential long-term consequences (Tripathi et al., 2024).

Nanotechnology from the Nose to the Brain in Migraine

A relatively recent technique for delivering medications to the central nervous system through the nasal canal is nose-to-brain nanotechnology (Lee & Minko, 2021). Because it can avoid the gastrointestinal tract and improve absorption, this approach is regarded as a possible substitute for conventional oral treatment. With this method, medications enter the brain through the nasal mucosa and go to the central nervous system via the olfactory and trigeminal nerves (K. Kumar, 2025). Numerous nano-delivery systems, such as liposomes, polymeric nanoparticles, nanoemulsions, solid lipid nanoparticles, and nanostructured lipid carriers, include migraine medications. The use of the pharmacological pharmaceutical barriers during the pharmacological barrier's, and over the pharmacological barriers, and over the pharmacological barrier's during some of the barrier's during the barrier's during the barrier's's, the pharmacological barrier's, pharmacological process.

Therefore, the nasal administration of drugs can significantly improve the treatment of migraine by delivering the necessary amount of drugs directly to the site of action (A. Kumar et al., 2015).

Nano-delivery systems are used in the management of migraines as they can help in transporting the drug molecules to the affected cells, thus solving some issues related to oral administration (Tanna et al., 2023). This method allows you to bypass most of the barriers in the gastrointestinal tract, which contributes to the rapid absorption of active substances. Besides, nano-systems are a great tool

in the fight against diseases due to their ability to retain and prolong the release of drugs. Therefore, nose-to-brain drug delivery is a promising and relevant technology for the treatment of migraine (Zheng et al., 2025).

But the efficiency of this technique is still in question. The nasal mucosa has a limited absorption capacity and there is a risk of the preparation being ejected from the nasal cavity. However, nasal irritation, instability of nano-carriers and toxicity of the particles themselves complicate this technology (Alghareeb et al., 2024).

(Gao et al., 2026)Although no evidence has been found for the short-term efficacy of this method, nose-to-brain technology may be a great tool in the fight against migraines. This goal, however, can be achieved if pharmacokinetic, safety, preclinical and clinical studies of this method are conducted.

Artificial Intelligence in Migraine Drug Delivery

Artificial Intelligence (AI) is an emerging technology that plays a critical role in migraine drug delivery. The concept AI covers computer algorithms that can take on pattern recognition tasks by processing large data amounts and making decisions on that basis. AI applications include drug discovery, formulation development, personalization of therapy, prediction of migraine attacks, and monitoring treatment progress. Coupled with advanced technology, it can provide new treatment options for migraine(Yadollahi et al., 2026a) .

Firstly, drug discovery and development with the help of AI is a breakthrough for personalized medicine. By using the AI, active compounds are identified, information related to pharmacological properties of the compounds can be integrated and the prediction of physicochemical properties like solubility and toxicity is done. AI can be used to accelerate the drug discovery process and to discover potential drugs for target indications(*Artificial Intelligence (AI) Applications in Drug Discovery and Drug Delivery: Revolutionizing Personalized Medicine - PMC*, n.d.-a).

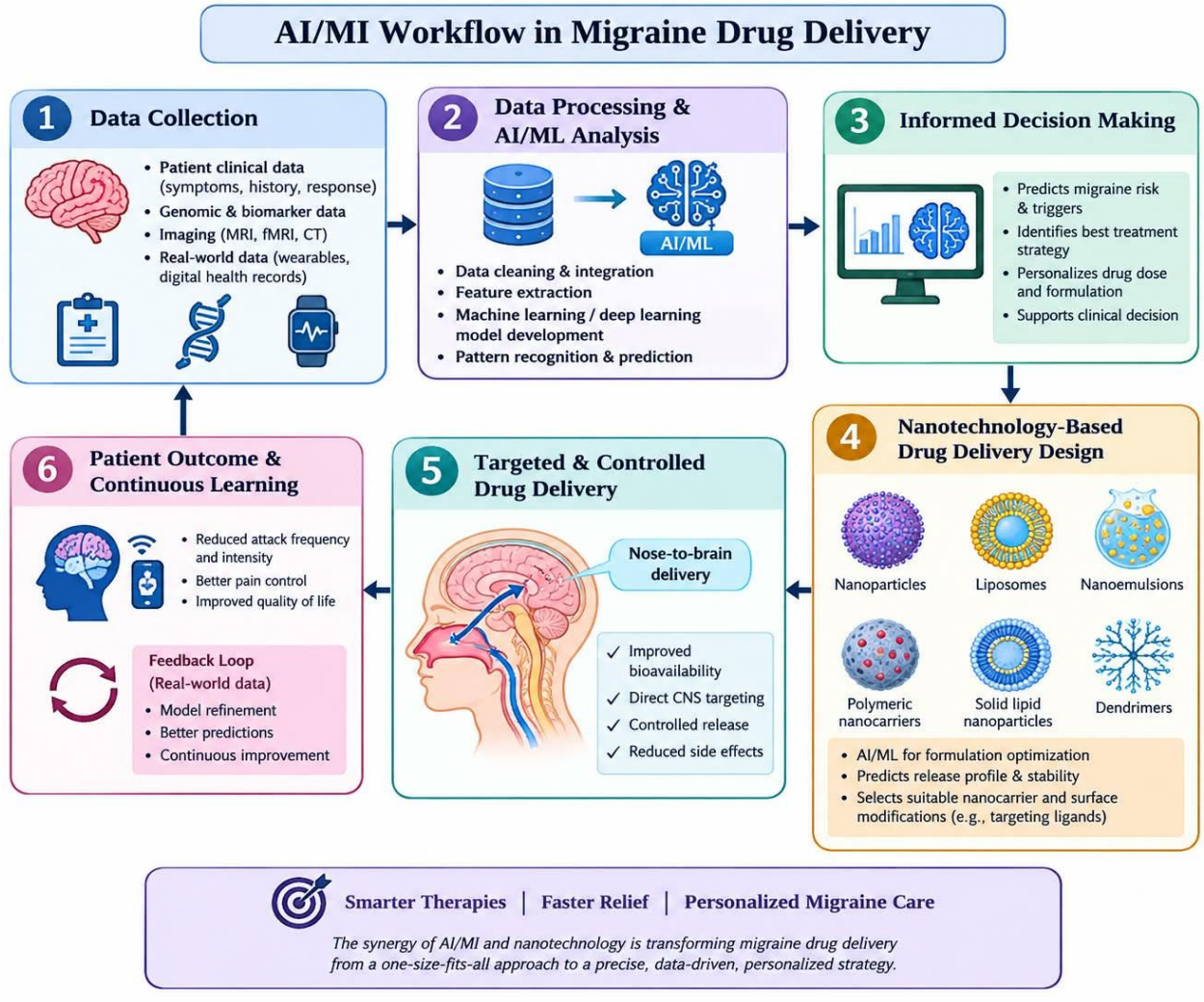

Figure-2: AI /MI Workflow in Migraine Drug Delivery

Additionally, the implementation of AI to facilitate formulation development processes continues to gain in prominence too. AI is able to assess a number of formulation parameters and subsequently determine the most beneficial variables in relation to positive patient outcomes. AI is set to integrate into the development of drug delivery systems to improve the production of formulations. Researchers are taking advantage of nanotech techniques for their effectiveness in increasing the impact of drug therapy in anti-migraine medications. With the application of AI technologies, it becomes possible to determine the beneficial parameters for the drug delivery formulation (Serrano et al., 2024).

Furthermore, AI can be employed to individualize the treatment of migraine headaches. Because of the fact that the migraine headaches are unpredictable and can vary extremely widely among patients, the individualization of the treatment is very important. With the help of AI algorithms, one can discover some patterns of patients' behavior and identify the best options for their treatment. Thus, the use of AI in treating of migraine headaches can improve the quality of life of patients due to a high degree of precision of personalized treatment (Giacon & Terrazzino, 2026a).

Moreover, AI that may predict future migraine attacks can also help with monitoring and treatment of the disorder. Patients will be able to provide information about their sleeping regimen, physical activity levels and heart rates to doctors via digital technologies. This data can then be employed to develop predictive models that identify possible triggers of a migraine, so that the patient can respond to an imminent migraine attack in a timely manner and ward it off with certain therapeutics (Yadollahi et al., 2026b).

And other potential applications of AI in migraine may involve nanotechnology drug delivery systems. At every step of nanoparticle development, AI can be incorporated, and help decide an important aspect such as particle size, drug loading, formulations, and release characteristics. Additionally, researchers can use machine learning's predictive capabilities to recommend effective materials for nanoparticle synthesis. This approach can help develop multi-functional drug delivery systems that will enable specific delivery of drugs (*Artificial Intelligence in the Design and Development of Nanoparticle Drug Delivery Systems: A Systematic Review - Haddad - 2026 - Advances in Pharmacological and Pharmaceutical Sciences - Wiley Online Library*, n.d.).

AI can also be used for intranasal and nose-to-brain drug delivery to optimize the formulation strategies. With the implementation of AI into preclinical and clinical research, conditions of nasal drug delivery can be established for the discovery of optimal formulation strategies such as viscosity, dose, and particle size of drugs to achieve high nasal absorption. Therefore, the utilization of AI is useful for the optimization of the drug delivery pathway to the brain (outside the systemic pathway) (Alwali et al., 2026b) .

Nonetheless, there are still major challenges that need to be taken into account before applying AI in treating migraines. Firstly, there is the requirement to do post-marketing surveillance studies to verify the data's accuracy and possibly eliminate part of the bias in AI. Moreover, physicians need to realize that treating based solely on prediction by AI can be harmful to patients' health.

Migraine management options with Artificial Intelligence The technology is primed to transform the drug delivery industry and empower clinicians to deliver the best standards of care to the migraineur. But, for such an approach to be embraced as a standard of care, large-scale preclinical and clinical studies are needed (Espinoza-Vinces et al., 2025).

AI + Nanotechonology Integration

AI and nanotechnology can work together to make drug delivery better for migraine treatment. AI starts by collecting information about the patient, the drug and the formulation. That information might include migraine symptoms, how the patient responded to treatment the properties of the drug and the features of the chosen nanocarrier (*Artificial Intelligence (AI) Applications in Drug Discovery and Drug Delivery: Revolutionizing Personalized Medicine - PMC*, n.d.-b).

Different AI techniques, such as machine learning, deep learning, predictive modelling and data mining can examine the information. Find patterns. AI can also help choose drugs and nanocarriers such as liposomes, lipid nanoparticles, polymeric nanoparticles and nanoemulsions. AI can optimize formulation factors like particle size, drug loading, surface charge, stability and drug-release rate. AI can cut down the number of experiments needed during formulation development (Gholap, Khuspe, Mane, et al., n.d.).

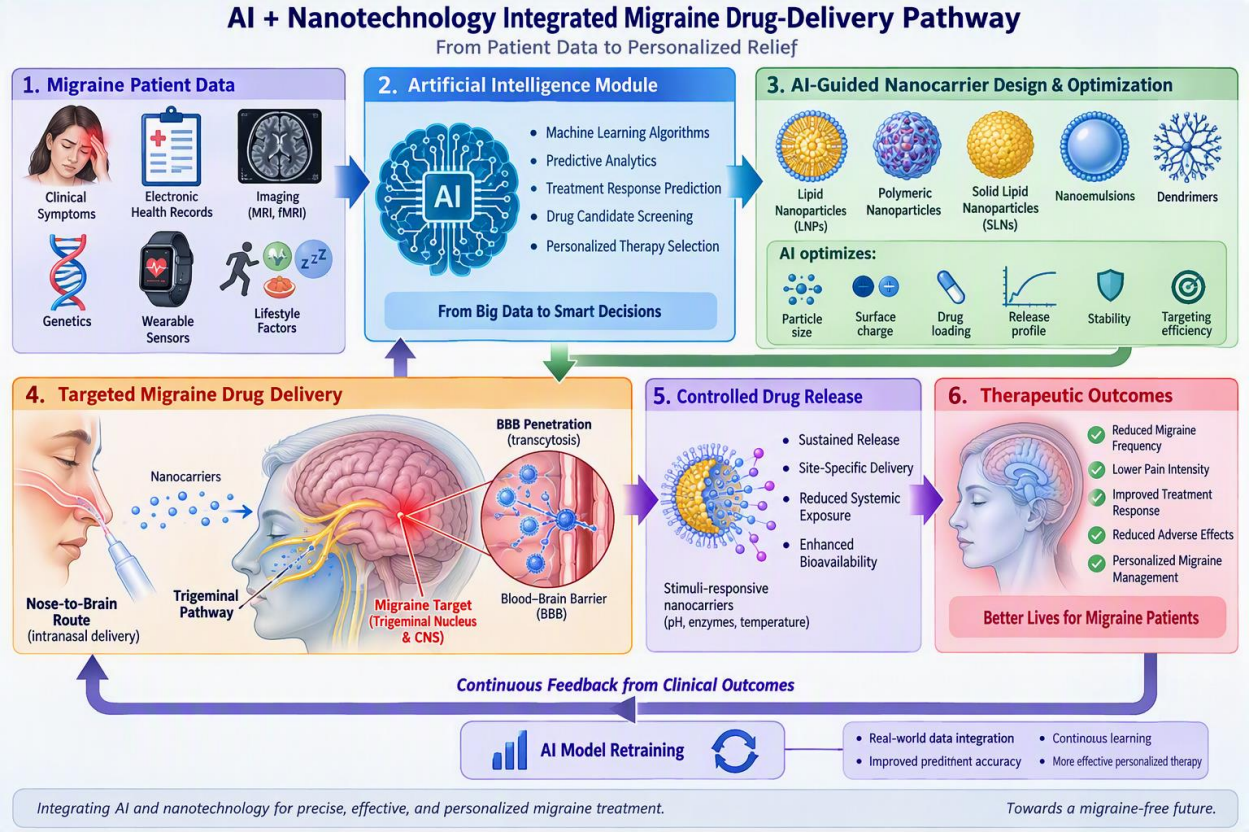

Figure-3: AI + Nanotechnology Integrated Migraine Drug –Delivery Pathway

After optimization the nanoformulation can be tested for its characteristics and drug-release properties. Nanotechnology can provide controlled or targeted drug delivery, which can increase drug availability and lower unwanted exposure to parts of the body. AI can track the patient's response by looking at migraine frequency, severity, duration and adverse effects.

AI can examine the collected information further to create a treatment plan. Newer approaches, like twins and generative AI are also being studied to predict how an individual will respond to treatment and to design new drug-delivery systems. However AI approaches such as twins and generative AI still need experimental and clinical studies before they become routine, in migraine treatment(Gholap, Khuspe, Mane, et al., n.d.).

Recent Trends in Nanotech and AI in Delivery of Medication for Migraine

Innovative innovations in migraine treatment these days include the use of combination of intelligence, nanotechnology, and tailored treatment for the betterment of the treatment.

AI and machine learning models are also being developed to predict a patient's response to prevention treatments for migraine. These can include history, symptomatology, previous responses to medications and other personal data. This may reduce the guesswork involved in selecting a drug (Yadollahi et al., 2026c).

Nano-carrier design Another application of AI is its use in the development of nanocarriers. Predictive modelling and machine learning are being used to improve variables such as particle size, drug loading, encapsulation efficiency, stability, and release rate to improve drug formulation efficiency. The method of intranasal nanoformulations are now introducing as fast drug delivery. The nose-to-brain delivery can be achieved for which drugs are directly targeted from nose to brain. Nanocarriers enhances solubility of drugs and enhances the residence time of drugs and also provide the sustained release through nasal route (Gholap, Khuspe, & Mane, n.d.).

If these types of drugs work at all they are often targeted to the site of infection and/or in a controlled-release nanosystem so that the drug is released only at the where it is needed. This should keep levels of the drug in the body for longer, may require less doses, and reduce side effects (Georgakopoulou et al., 2024).

Data-driven personalized therapy involves selecting the appropriate treatment for a patient and modifying it based on its effectiveness and any related side effects. This process provides

individualized therapy tailored to the patient's requirements (Ciftci et al., 2025).

Finally AI is giving a helping hand to bring together various kinds of data - ranging from clinical data to medical images to patient-recorded electronic headache diaries and data from wearables. By combining all of these, AI enables prediction and continuous monitoring and more tailored treatments for migraines (Petrušić et al., 2025a).

Pros of Utilizing AI and Nanotechnology in Migraine Medication Drug Delivery systems

- The use of AI and nanotechnology has many potential advantages for headache treatment.
- Enhanced solubility and bioavailability: Nanocarriers can improve the solubility and absorption of drugs with poor water solubility leading to an increase in their bioavailability.
- Controlled and sustained release: Drugs in various forms of Nanoformulations are released at a slower rate that makes them more effective and may help to decrease the number of doses needed (Maleki Varnosfaderani & Forouzanfar, 2024).
- Targeted delivery: Nanocarriers can be engineered for site-specific drug delivery to particular tissues or cells.
- Less systemic exposure: Targeted delivery may limit undesired distribution of drugs throughout the body and may decrease systemic adverse effects.
- Fast onset: Some nanoformulations, such as intranasal delivery systems, could allow for faster drug absorption and faster relief during migraine attacks (Rawool, 2026).
- Formulation optimization: Using AI and machine learning to evaluate various formulation factors and to forecast best sets of formulation, minimizing the lab testing.
- Personalized therapy: Individualized drug and dose selection with the help of AI, based on a patient's properties, medical history and treatment response data (*Nanoparticles as Drug Delivery Systems: A Review of the Implication of Nanoparticles' Physicochemical Properties on Responses in Biological Systems*, n.d.).

Challenges and Limitations

The concept of using artificial intelligence (AI) and nanotechnology in medicine for the treatment of migraine is promising but still there are a number of obstacles to consider before such methods could be implemented in practice.

To guarantee the safety and compatibility of nanoparticles with the human body, extensive research and testing of nanocarriers should be done first. They can have a neurotoxic effect, as is well known. Targeted therapy will undoubtedly become more effective with the introduction of highly functional nanoparticles, but there may be safety issue (Torrente et al., 2024).

A further problem in the implementation of this method is related to the reliability of delivery mechanisms. Such carriers may help in delivering medication directly into the brain, however their' effect on the blood-brain barrier should also be investigated. The effectiveness of treatment is strongly dependent on the properties of the nanoparticles, e.g. their size.

In addition, there are no clinical studies confirming the effectiveness of this treatment methodology. Currently, much of the research into applying AI to migraine treatment and drug development is in its early stages. So there is not enough data on the long term impact (Hersh et al., 2016).

One of the biggest obstacles in artificial intelligence is the volume of data required for training. These data include patient statistics for migraine treatment, which are currently inadequate and vary from case to case. Furthermore, the algorithms must be accurate and efficient enough to handle the current data (Petrušić et al., 2025b).

These days, integrating these two contemporary medical advancements presents a number of difficulties for researchers. In addition to the challenges with data quantity and quality that have already been discussed, there are problems with the cost of manufacturing medications. A dependable and proven production method is necessary to Researchers should also aim to develop standardized procedures for clinical investigations which will improve the comparability of their findings. However, the use of AI in medical practice raises ethical and legal concerns which researchers have to deal with (Martínez-García & Hernández-Lemus, 2022).

Therefore, before utilising AI and nanoparticles in migraine therapy, a number of issues must be resolved. Even if these projects have a lot of potential, they can only be realised if researchers from several professions collaborate and work together to find trustworthy data sources, design efficient algorithms, provide reasonably priced medications, and acquire sufficient outcomes in investigations (Y. Kumar et al., 2023).

Future Perspectives

The future of migraine drug delivery is likely to be heavily impacted by artificial intelligence (AI), machine learning (ML), nanotechnology, and personalized healthcare. Traditional drug delivery methods may not be able to provide rapid and uniform therapeutic effects in all patients. Thus, there is an exploration of innovative technologies for improved drug absorption, bioavailability, targeting and therapeutic response (Giacon & Terrazzino, 2026b).

The future will see an important aspect in the use of AI-assisted nanocarrier design for migraine-drug delivery. AI and ML algorithms can evaluate large datasets of formulation data to predict key properties such as particle size, encapsulation efficiency, drug loading capacity, stability and drug-release behavior . This could greatly reduce the need for tedious trial and error experiments and ease formulation development. Artificial intelligence can also be used to identify the right combinations of drugs, polymers, lipids, surfactants and other excipients (Alsaqabi et al., 2026).

Delivery of drugs to the brain via the nose is a promising route that may provide rapid drug absorption, with the potential to improve delivery to the central nervous system through the olfactory and trigeminal nerves. Further studies could be oriented toward the design of mucoadhesive and controlled-release nanocarriers, nanoemulsions, liposomes and lipid-based systems to increase nasal residence time and improve drug transport (Gandhi et al., 2024).

Furthermore, synergy of AI with Quality by Design (QbD) can assist formulation development by understanding critical material attributes and critical process parameters as well as predicting critical quality attributes.

One of the most important future aspects in migraine management is individualized treatment. Triggers, severity, treatment response and the medicines required can be dramatically different from one migraine sufferer to another. AI-based systems can evaluate patient features, treatment history, clinical outcome and other data to identify the right drugs and delivery systems for each individual. In the future, personalized nanomedicines may provide therapeutic regimens tailored to the patient, with the right doses and controlled release of drugs (*Artificial Intelligence In Pharmaceutical Formulation Development: From Quality By Design (Qbd) To Autonomous Drug Design | Zenodo*, n.d.).

Smart nanocarriers will be an important part of the future of migraine drug delivery. Stimuli-responsive nanocarriers can be used to achieve an improved therapeutic efficiency with a reduction of unnecessary drug exposure. AI tools can be used for the design of smart nanocarriers and prediction of their behavior.

However, there are several challenges to be addressed such as limited and inconsistent datasets, AI model validation, toxicity, long-term safety and reproducibility, manufacturing scale-up, cost and regulatory approval. Predictions made by AI models need to be validated clinically and experimentally before they can be implemented (K & Yazeed, 2026).

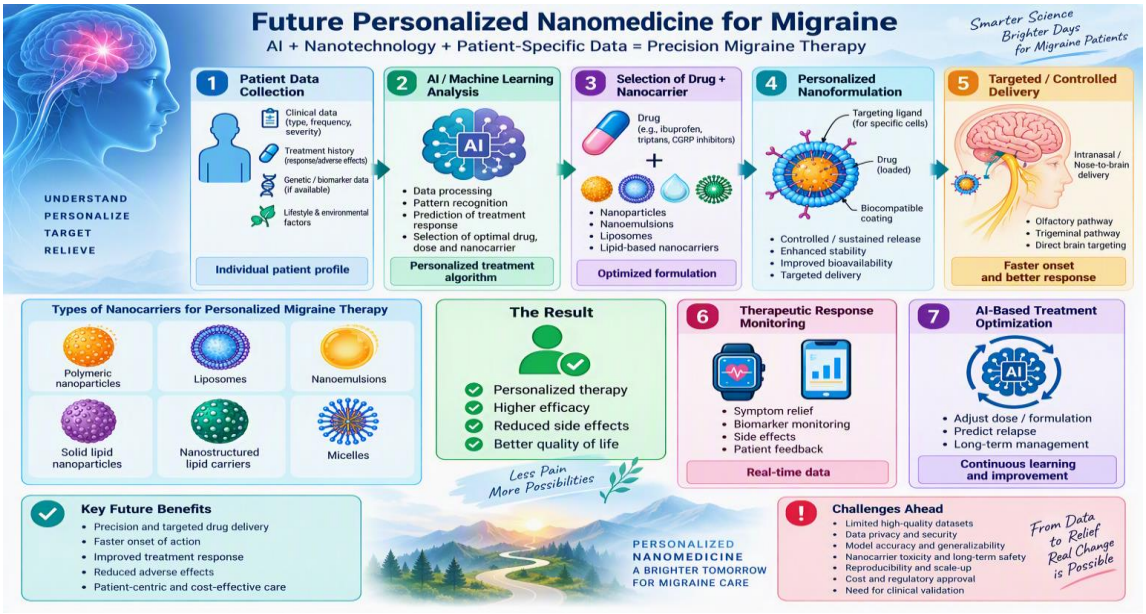

Figure-4:Future Personlized Nanomedicine For Migraine

Overall, the convergence of AI, nanotechnology, nose-to-brain delivery, QbD and personalized healthcare holds the potential to transform the future of migraine-drug delivery. Future research should focus on reliable data set, explainable AI, standardized characterization of nanocarriers, preclinical studies and well-designed and powered clinical trials to enable future breakthroughs in this exciting area (Huang et al., 2024).

CONCLUSION:

Artificial intelligence and nanotechnology are emerging as novel and promising strategies to ameliorate the delivery of migraine drugs. Conventional drug delivery system suffers from problems like low solubility, poor absorption, delayed onset of action and systemic side effects.

The use of nanotechnological approaches such as nanoemulsionsPolymeric nanoparticles, liposomes, solid lipid nanoparticles, nanostructured lipid carriers, and intranasal and nose-to-brain delivery systems can enhance drug solubility, stability, bioavailability, controlled release, and targeted delivery.

In contrast, artificial intelligence and machine learning can help to design and optimise the formulations and delivery systems based on the desired physicochemical properties of the particles like size, drug loading content, encapsulation efficiency and stability.

Furthermore, standard artificial intelligence can be helpful to forecast the drug release, pharmacokinetics and overall performance of various dosage forms Nanotechnology together with AI and quality by design concepts can reduce the trials and errors during the design process and provide better formulations with improved function, flexibility and scalability.

One of the most important applications of AI in migraine management is personalised treatment, which can be made possible by determining the best treatment option for each individual patient according to their characteristics and preferences.

But there are still barriers to overcome, including limited data sets, toxicity, batch consistency, upscaling, clinical evaluation, costs, and regulatory approval. It can be generally concluded that Challenges still to be addressed are limited datasets, toxicity, batch consistency, upscaling, clinical evaluation, costs and regulatory approval.

To summarize, the combination of artificial intelligence, nanotechnology and personalized healthcare will be able to revolutionize the creation of more effective and specific migraine medication delivery systems in the future.

Conflict of interest

None

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