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Impact of Emerging Technologies in The Development of Personalized Medicine

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Abstract

Personalized medicine refers to the production of medications suited to each patient's unique traits, such as their genetic composition, to provide more effective and focused therapy. Emerging technologies ' have had a significant impact on personalized medicine's growth and hold promise for more individualized, accurate treatments. This review offers a thorough analysis of the role of modern technologies in the developing area of customized healthcare by addressing both the potential and the challenges. The technologies investigated in this study are genomic sequencing, Artificial Intelligence (AI), Nanotechnology, Organ-on-Chip, and stem cell technology. The methodology used is data analysis of various authentic databases available online. By advancing our knowledge of unique patient profiles, each of these technologies helps create treatments that are more successful and less likely to have side effects. This study also looks at how various technologies might be combined to enhance their overall influence on medication development by complementing one another.

Key words: Personalized medicine, Artificial Intelligence, Genomic Sequencing, Nanotechnology, Stem Cell, Organ-on-Chip, Drug development

Introduction

A vast constantly developing area of health care, precision or personalized medicine, is based on the individual clinical, genetic, genomic, and environmental data of every patient. Personalized medicine applies our molecular understanding of diseases to optimize preventative health care methods, but it also depends on interdisciplinary health care teams as well as collaborative technologies. [1]

An early introduction to the concept of personalized medicine was done by Weber's 1997 book, which provides an excellent overview of the pharmacogenetic properties of drugs as well as genetic variants in genes that affect the efficacy and side effects of drugs, particularly regarding genetic variants in drug metabolizing enzymes. [2]

Let us take Warfarin as an example, it is a commonly used blood thinner that requires careful dosing due to the risk of life-threatening reactions. It targets the VKORC1 gene and is partially metabolized by the CYP2C9 gene. Genetic variations in these genes lead to differences in how individuals respond to warfarin, affecting its pharmacodynamics and pharmacokinetics. As a result, the FDA recommends personalizing warfarin dosing based on an individual's VKORC1 and CYP2C9 genotypes.[2]

The fundamental value of personalized medicine in the pharmacy sector is its ability to minimize side effects, improve therapeutic efficacy, and maximize treatment outcomes. [3]

Personalized medicine has the potential to enhance health outcomes and minimize expenses; however, it calls for cooperation from multiple stakeholders, including patients participating in clinical trials, physicians understanding diseases at the molecular level, the IT industry by developing algorithms to gather and safeguard patient data, policymakers considering novel business models, investors, and, above

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all, the researchers developing new technologies in the production of personalized medications.[4]

The advancement of patient care through cutting-edge technologies is a major force behind the emergence of personalized medicine. Artificial intelligence (AI), organ-on-chip systems, genetic markers, nanotechnology, and stem cell research are some of the major breakthroughs in these fields. [Figure 1] As we investigate these technologies, it becomes clear how they deepen our knowledge of illnesses and make it possible to pinpoint therapeutic pathways. Healthcare professionals can give more targeted treatments, minimizing trial-and-error methods and enhancing patient results, by combining various technologies. The combination of these technologies signifies a radical change in the way we see patient care and medical treatment.

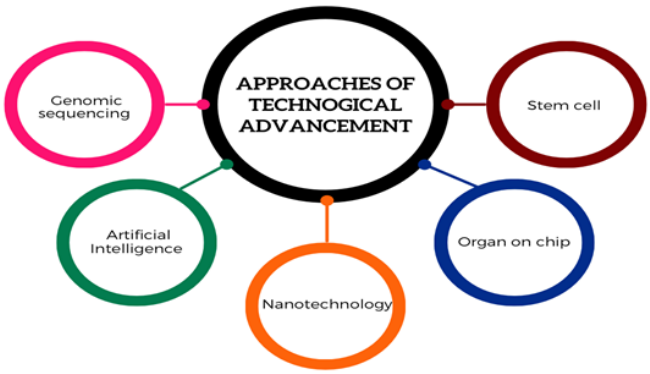


Figure 1

Materials and Methods/ Headings

This study uses a literature review methodology to overview technologies in personalized medicine. A systematic search of databases like PubMed and Google Scholar will use keywords such as "personalized medicine, genomic sequencing, artificial intelligence, nanotechnology, organ on chip, stem cell therapy." The review will include peer-reviewed articles until December 2024, focusing on technological advancements and relevant case studies. Data will be synthesized to identify key themes, with case studies illustrating practical applications. Limitations will be noted, and findings will enhance understanding of technology's role in personalized medicine while suggesting future research areas.

Results

1.1 Genome sequencing

One of the most significant advancements toward personalized medicine can be credited to the rise of genomic sequencing in modern-day therapeutics. Genome sequencing refers to the method of determining the entire genetic makeup of a specific organism. It provides the extensive assortment of an individual's genetic variation, including the order of all, or most, of the nucleotides in an organism's DNA. The sequencing of genome serves as a key tool for large-scale gene identification, cloning, and analysis, and can contribute valuable insights into biological functions, disease mechanisms, and evolutionary relationships. Additionally, examining sequence data at community level allows public health authorities to track how microorganisms circulate through populations and undergo changes over time. [5,6,7]

Although different sequencing techniques might incorporate the use of distinct procedures, technology and have different requirements, the basic process of genomic sequencing is as follows. Primarily, strands of DNA or RNA are extracted from the test subject. They then undergo special preparatory measures based on the sample and relevant equipment (for example, conversion of RNA to DNA or snipping the strands into smaller pieces with desired lengths or modifying the ends of the fragments to meet the requirements of the sequencer). These customized samples are referred to as 'library' and are loaded in the 'sequencer.' The sequencer is a device that identifies the nucleotide bases in the DNA fragment through various methods, such as by reading fluorescent signals or by incorporating electric current and monitoring changes. A large amount of data consisting of millions of strings of letters are then produced displaying specific nucleotide sequences, this can be compared to the preinstalled referential sequences to identify variations in the sample via analytic programs. This sequencing of genomes has paved the way for numerous studies that have improved our understanding of biological processes and molecular mechanisms.[8]

Genomic sequencing has significant application in personalized medicine. It contributes to earlier and more accurate diagnosis of disease risks and epidemiology, supports prevention and personalized treatments, aids in monitoring the health of both healthy and treated patients, and plays a key role in preventing future diseases and their recurrence. As we know, genetics hold immense significance in our life because slight changes in a specific gene corresponds to prospects of various threatening diseases such as cancer, coronary diseases, diabetes etc. Observation from gene sequences sparks the arena of personalized medicine, by providing tailored treatments based on an individual's genetic background. Genomic sequencing can identify genetic mutations or variations that increase an individual's risk for developing certain diseases even before symptoms appear, enabling early intervention or preventive strategies. It can also be used in predicting an individual's response to specific medications based on their genetic makeup. This is known as pharmacogenomics. By matching patients with the right drugs and the right doses based on their genetic profiles, pharmacogenomics helps reduce adverse drug reactions, improve drug efficacy, and lower healthcare costs. It is also likely that these technologies will be utilized in clinical biomarker testing, particularly when complex, potentially temporal, or multivariate biomarker profiles are employed to enhance diagnostic accuracy. [9] Another intriguing application of this technology is the use of 'Tumor Genomic Profiling' that can determine specific mutations in the DNA of cancer cells. Personalized biomarkers, most likely to be effective based on the genetic characteristics of the tumor can then be administered. [10] Moreover, gene therapies can be sought in case of an identified mutation and gene editing technologies (like CRISPR) with the aim of correcting or replacing the faulty gene can be used. New Generation Sequencing is also anticipated to assist in clinical applications of diseases such as retinitis pigmentosa, inflammatory bowel disease, neurofibromatosis, dilated and hypertrophic cardiomyopathies and many more. [9]

As this field and technology progresses, there are a few modifications required for thorough adaptation and implementation. These include the necessity of researchers and clinicians to familiarize themselves with recent developments and new tools as they are constantly being upgraded.[11] The development, standardization, and integration of several important tools (such as health risk assessment, family health history etc. into health care systems is also imperative. Moreover, the computational resources required must be accessible in terms of costs, skills, and efficiency. It is also important to keep in mind that there is still much room for improvement in these technologies. [12]

1.2: Artificial Intelligence

As more drugs are being produced, the potential of interactions also rises thereby raising the significance of patient safety and efficacy of treating regimens. Other earlier approaches of determining such interactions include clinical trials and accumulate evidence, hence inadequate in a setting that majority of patients are on multiple drugs. Recent improvement in machine learning presents an exciting direction for improving our ability to forecast future drug interactions.[13]

Machine learning models can reveal hidden or complex relationship between data sets containing chemical properties as well as biological and clinical information. These predictive models can act as effective instruments for the healthcare managers and practitioners making decisions to be able to understand the needs of a patient to fit a particular treatment.[13]

The process for training and selecting machine learning models for drug interaction prediction involves several key steps. First, data is retrieved, encompassing drug interactions along with relevant chemical, biological, and clinical information. Next, data cleaning is performed to address issues such as incorrect labelling and missing values, followed by the extraction of key features like molecular properties and interaction context. Finally, suitable algorithms are chosen for model selection. [13-15]

These models will be discussed briefly in Table 1 and 2 to improve the prediction for the conditions of drug interaction and patient safety. [16-23] (Table 1, Table 2)

Supervised Model		Advantage and consideration
Random Forests	An ensemble method that constructs multiple decision trees during training and outputs the mode of the classes (classification) or mean prediction (regression).	They are effective in predicting drug interactions due to their resistance to overfitting and ability to handle large datasets with many variables. They also help identify feature importance, highlighting drug properties or patient characteristics linked to breakthroughs or increased interaction risks May require longer training times and careful tuning of hyperparameters compared to simpler models like SVM
Support Vector Machines (SVM)	Support Vector Machines (SVM) are supervised learning models used primarily for classification tasks, although they can also be adapted for regression.	SVM is effective for high-dimensional medical datasets, utilizing multiple kernel functions to capture various relationships among data vectors and decision boundaries Training can be time-consuming, especially with large datasets, as the algorithm solves a quadratic optimization problem. The impact varies based on the kernel and its parameters, which may require careful tuning to optimize SVM performance
Neural networks	Neural networks are computational models inspired by the human brain, consisting of interconnected layers of nodes (neurons). These networks learn representations from data through a process of adjustment based on input-output mappings.	These networks learn from data by tuning to input-output mappings, identifying hierarchical features in chemical structures and patient details. This flexibility enhances drug safety and treatment evaluations in pharmacology, improving prediction accuracy and supporting clinical decision-making. It often requires substantial amounts of data, which can be scarce in areas like pharmacology. Training them is time-consuming and demands significant computing power

Table 1: Discussing supervised model of machine learning [16-20].

Unsupervised Model		Advantage and consideration
Clustering Techniques	Clustering refers to a method through which many records are grouped into segments based on their similarities, Thus, if there is interest in a specific cluster of various variables, for instance, potential drug collaboration, research work will be more effective.	Further investigation into specific clusters, improving the efficiency of research efforts in predicting potential drug interactions. Furthermore, these methods are computationally efficient, which will enable them to work with sample sizes typical of pharmacological research. Clusters can be difficult to interpret for those unfamiliar with the domain, leading to misinterpretations of their clinical relevance
Dimensionality Reduction Methods	Dimensionality Reduction Methods Dimensionality reduction techniques such as PCA and t-SNE compress data with high dimensions to fewer variables while retaining vital relationship	Emerging visualization tools like PCA and t-SNE improve the analysis of high-dimensional drug interaction data. By highlighting valuable features, these methods help clarify how certain drug properties relate to interaction risks, enhancing decision-making in drug safety Although PCA is used in analyzing linear relations, it can sometimes mask nonlinear correlations necessary in analyzing drug interactions.

Table 2: Discussing unsupervised models of machine learning [21-23].

The utilization of such algorithms and machine learning can help researchers identify new therapeutic outcomes as well as enhance the patient experience. In this case, AI plays distinct functions; for instance, to find the most suitable compound in an extensive pool of chemical substances and to estimate drug interactions or design exclusive treatment plans for every patient. [16-18]

A prominent use of AI in drug design is on the identification of potential drug-target interactions. This technique involves using a database of the structural molecular and biological data to train an AI to observe patterns that would help determine the nature of an interaction between a drug molecule and the target protein. This enables the rapid elimination of outsized populations of compounds in search of molecules with high binding affinity and selectivity for the target of interest. [19-23]

In addition, other applications of AI discussed include further optimization of new drug molecules. Since several algorithms that may predict and analyses a molecule's structure are available, the researchers can optimize and alter the drug candidates for high binding affinity, bioavailability, and low toxicity. This makes it possible to make several modifications to a drug design in a short span of time since it is easier to simulate the outcomes compared to practical human testing.[24]

The concept of structure–activity relationship (SAR) is based on the opinion that similar structures of molecules behave similarly in their biological activities. SAR can predict the biological behaviour of the drug with the help of regression model which is used to compare the structural feature of a set of known related ligands that has potency for the desired activity, for example, binding to the target receptor or inhibiting an enzyme. Using SAR models one can predict if incorporation of chelators, radioactive ions or chemical groups into the bioactive substance will affect the binding characteristics and efficiency of a proposed radiopharmaceutical or lead to its interactions leading to toxicity or unsuccessful binding. [24-25]

In conclusion, the changes resulting from personalized medicine and data-assisted technologies, big data, and AI are taking place across the biomedical spectrum. These themes not only increase the accurate of medical approaches but also increase the results of the patients making health care more efficient and effective.

It is anticipated that the application of AI and big data analytics to pharmacogenomics research will advance personalised medicine and healthcare. The use of big data analytics and artificial intelligence (AI) can produce useful insights from the trends seen in pharmacogenomics data in the context of medication development and personalised treatment. This involves developing medications, predicting their efficacy, introducing medical devices, and implementing treatment plans with algorithms utilising machine learning, deep learning, and related technologies. With the ability to test life-saving medications, offer knowledge in advance, and target the community-level impact of pharmacogenomics implications, even on a population, the integration of big data analytics and AI in pharmacogenomics is viewed as a paradigm change in health trend. For example, AI and machine learning approaches enable virtual chemical screening, in silico medication reconfiguration, and the detection of risk genes for disease-causing mutations, all of which contribute to the progress of personalised medicine and discovery of drugs. [26-28]

However, using AI in personalized medicine brings challenges, ensuring data privacy and security is a major concern, as patient information is overly sensitive and must be carefully protected. Additionally, AI systems are only as good as the data they are trained on, and if that data is biased or incomplete, the AI may produce inaccurate or unfair outcomes. [29-31]

For instance, lactate can be a good indicator of mortality rates but if only the limited number of patients undergo this test, then it does not paint the true picture of all the patients.[31] In its turn, this may affect the generalization of the results to the complete population of cases and reduce its accuracy due to a limited sample of values that took place to be chosen. This is a good illustration of how data access and sampling traditional bias affect the quality of AI in delivering health care. In personalised medicine this can mean that factors which help in predicting risk of death for underrepresented groups do not emerge in the training set, and the model learns to predict illnesses that are tested for more frequently. [32-34]

1.3 Organ-On-Chip

Organ-on-a-Chip (OoC) technology is rapidly advancing due to progress in stem cell research, enabling the development of microfluidic devices that mimic human organ functions. This innovation supports drug development, disease modelling, and personalized medicine.[35]

Developers select primary cells, stem cells, or cell lines that best mimic the target organ, growing them under specific conditions to promote growth and differentiation. Successful cell culture is essential for the OoC system's functionality.[35]

The process is followed by the implementation of cells in the chip. This includes the establishment of transferring the prepared cells into the microfluidic channels so that they have a uniform distribution on top of the channels and the most importantly good adhesion onto the substrate. An extracellular matrix (ECM) coating provides structural support, anchoring the cells. To mimic natural physiological conditions, microfluidic flow simulates blood circulation, while controlled delivery of nutrients, temperature, humidity, and gas concentrations create an environment that supports cell function. [35-37]

The first step in implementing the OoC (Organ-on-Chip) system involves assessing cellular characteristics such as morphology, viability, and biochemical markers. Experimental measurements focus on drug responses, toxicity, and compound effectiveness, with real-time monitoring of cell behaviour and metabolism using integrated sensors. Advanced statistical tools analyse the data, aiding validation, and the development of reference compounds for accuracy confirmation.[37]

The applications of OoC technology provide a unique opportunity for modelling that can be used in preclinical drug development to determine drug efficiency and potential side effects in human models. These devices are flexible at every phase of the medicinal development process, from easy, high-speed models at early preclinical periods to complex multi-organ systems at later.[37]

For instance, Barrier tissue chips enable researchers to observe how drugs are absorbed and transported across barriers, a process essential for understanding a drug's bioavailability. This includes: [38-40]

- Gut-on-a-Chip: This model has human intestinal cells that replicate the intestinal barrier plus an aperture for microfluidic motions resembling the kind of peristaltic movements, which enable researchers to observe the transit of orally administrated drugs in the gastrointestinal terrain.

- Blood-Brain Barrier (BBB)-on-a-Chip: The BBB is famously restrictive, admitting only specific materials into the brain from the bloodstream. BBB-on-a-chip models are particularly valuable in predicting whether drugs can penetrate the blood–brain barrier and thus are incredibly useful when developing treatments for neurological disorders.

Multi-Organ Chips (Body-on-a-Chip) link several organ models in one system so that researchers can investigate how organs interact with each other. For example, liver-kidney-heart multi-organ chips show how a substance circulates and behaves on multiple organs in the body. Such parallel testing utilizing several organs in the body, sometimes yields diverse results and such interactions can thus be anticipated and averted where necessary. [41-43]

For example, after being metabolized by the liver, a drug might interact with the kidneys or heart, leading to side effects. This type of multi-organ testing can reveal unexpected reactions, helping prevent harmful outcomes. [41-43]

OoCs have more sophisticated sensors and imaging in real time of cell and tissue reaction to drugs. These sensors assess variables like, electrical activity, acidity, oxygen, and metabolic process changes. Unlike traditional testing methods that rely on end-point measurements, OoC systems allow for continuous tracking of changes over time. This approach is particularly useful in identifying delayed toxicities, or in observing the gradual effect of a drug on cellular behaviour.[44]

Everyone has his or her health needs and risk factors that are defined by such factors as behaviour, eating habits, metabolism, heredity, and conditions in their environment. These factors define individuals' susceptibility to diseases and their responses to specific treatments. Tissue biopsies, residual tissue specimens after surgery, and blood, stool, or urine samples from patients are the easiest techniques to develop an individual organ-on-chip. OoC treatment in corrective care makes it possible for health care givers to keep the characteristics of the patient in focus as they design their plans. [44-46]

Research studies have demonstrated that blood samples from selected subjects can be utilized in blood vessel-on-a-chip models with non-activated endothelium and reduced vascular tissue, allowing for the assessment of platelet coagulation and thrombosis following endothelial activation. Most importantly, the chips derived from patients on antiplatelet medications such as aspirin and clopidogrel had lesser thrombosis when compared to the control, thus perfectly demonstrating the differentiation capability of the chips between the individual response to drugs.[46]

In sickle cell disease, flow velocity was infinitely variable on blood samples in a manner characteristic of the diseases. Yet these oscillations became constant when the blood from the patients who received hydroxyurea treatment was circulated through the chips. Since acquiring the primary patient derived tissue sample is challenging patient stem cell models are a great asset. [46,47]

Skin fibroblasts, mononuclear cells from blood, or renal epithelial cells from urine could be directly reprogrammed into human induced pluripotent stem cells (hiPSCs) with the use of four transcription factors only for a limited time. Some of the hiPSCs can theoretically developed into any tissue type while they still carry genetic code of the initial donor. Long term purpose- Integration of an array of OoCs into a complex, systemic model Organ-on-chip technologies for modelling the musculoskeletal system could improve upon existing research methods by replacing animal testing. It can propel the drug discovery in the pharmaceutical company and on the other side improve the testing with more efficiency and preciseness. Also, the integration of these models into one system requires creation of fully automated medical procedures, which will minimize errors and maximize the accuracy of treatment. [47-49]

This innovation could dramatically reduce the potential of mistreatment of patients in the health practice, while making it possible to prescribe therapy as per patient need. Finally, an integrated and evolved form of OoC system becomes a kind of humane, non-waste, and optimized medical system.[49]

Current organs-on-chips (OOC) are used for drug testing and disease research but adapting them for precision medicine requires overcoming substantial challenges. However, expanding their use to precision medicine requires overcoming several complex challenges. Thus, to match each patient's condition for better treatment many OOC models must be produced at large scale to be affordable, fast, and practical for real-time clinical application. This requires important enhancements in different fields such as optimal stem cell differentiation methods, the effective sample preparation, personalised device fabrication, and sophisticated software that could adapt the cell culture conditions according to every patient needs. However, the methodologies for developing models from the patient-specific data set in the context of multiple cell types and culture environments are technically demanding and expensive. These obstacles underline the need for further technological advancements to make personalized organs-on-chips a viable tool in precision medicine. [44,49,50]

1.4 Nanotechnology

Nanotechnology and the development of nanoparticles have expanded during recent years and are being used in a broad range of clinicals. Nanoparticles have been produced to overcome the drawbacks of free therapies and overcome biological barriers that vary depending on the patient population and condition. These barriers can be systematic, microenvironmental, or cellular.

Nanotechnology involves engineering materials on a nanoscale; for 10- 100 nanometers. Targeted delivery of drugs, stability and enhanced properties are some unique properties for this method. And these properties are developed in drugs by pharmaceutical industries for the drugs to be more efficient, minimal side effects and tailored according to individual needs [51-52]

In personalized medicine, it is an approach aimed to target the right drug with the right dose and to the right patient, which is navigated by factors like variability in the drug efficacy and adverse drug effects. Nanosensors help with early detection of a disease and monitors continuously, which provides real-time feedback that aids in dynamic, tailored treatment adjustments. Nanoparticles drug delivery has proven to be useful in many aspects like gene therapy, AIDS therapy, cancer therapy and radiation. Furthermore, it can be used to serve as vehicles to cross blood brain barrier, antibiotics, vaccinations, and transport proteins. These precisions align ideally with personalized medicine's goal of making individualized plans for treatment, minimizing the risks associated with traditional therapies while optimizing health outcomes. These technologies are going to grow even more significant in delivering safe, more efficient, and more patient-centered treatment plans as research into them keeps proceeding [53-54]

Nanotechnology crucially enhances drug delivery using nanocarriers, like nanoparticles, lysosomes, and dendrimers. Which enables the target delivery of drugs specific tissues and cells, alongside maximizing therapeutic efficacy and minimizing systemic toxicity. Traditional drug therapies may often affect both healthy cells and diseased cells, which causes side effects that hinder treatment outcomes and reduce patient compliance. Nanocarriers are developed to deliver drugs to specific cells, bypassing healthy tissues and reducing adverse effects. In oncology, this approach is valuable, where side effects and drug resistance from conventional chemotherapy remain significant challenging [55].

For instance, a study done recently explores the use of albumin bound nanoparticles which is engulfed with paclitaxel to specifically target tumor cells, which highlights the reduced toxicity in non-cancerous cells and an increased concentration of drug in tumor tissues. Furthermore, liposomal doxorubicin, like doxil, showed efficacy in treating ovarian and breast cancers with comparatively fewer side effects than traditional doxorubicin therapy. By improving drug delivery precision, nanocarriers not only enhance the effectiveness of the treatment but perfectly align with the goals of personalized medicine, which offers options for customized therapies [53-55].

Pharmacogenomics is also a key component of personalized medicine. By making it possible to create nanoparticle-based biosensors that can swiftly and effectively assess their genetic information to predict specific medication reactions, nanotechnology has significantly improved pharmacogenomic testing. As it enables the physician to customize the drug therapies according to the patients' genetic profile, this ability is crucial for personalized medicine and improves treatment effectiveness and safety [56,57]

A recent study about magnetic nanoparticles that could isolate DNA for analysis of rapid pharmacogenomics, which identifies the gene variants that affect the metabolism of the drug. Because of this development in nanotechnology, point-of-care genetic testing is now possible, allowing physicians to make faster and effective treatment plans. By this, the healthcare providers can customize plans of treatment in regard with the individuals' unique genetic makeup, personalized medicines' core principle [56-57]

Early diagnosis and monitoring are made easier by the sensitive instruments that nanotechnology has developed for identifying illness indicators at low quantities. Assays based on nanoparticles and nanosensors detect certain biomarkers in blood or tissue, giving vital information for prompt action. According to recent research, certain nanosensors can identify molecular biomarkers in individuals with prostate cancer, while others may detect cancer-associated proteins at picomolar concentrations using particular antibodies. Personalized medicine is supported by this early and precise detection capabilities, which makes it possible to create treatment programs that are specific to each patient's illness development.[52,58]

One of primary benefits of nanotechnology in personalized medicine is its ability to minimize medication toxicity, particularly in chemotherapy. To minimize damage to healthy cells, drugs are contained in nanoparticles that release their contents at specified target cells. Lipid-based nanoparticles that increase the tolerance of hazardous immunotherapy medications are covered in a recent study. Compared to conventional techniques, this precise targeting reduces side effects by 50% and produces more effective and bearable therapies. [59,56]

Real-time monitoring of treatment reactions is made possible by nanosensors that detect biomarkers. This enables customized medicine to make quick modifications to guarantee the safest and most efficient doses. Nanotechnology monitors blood glucose in diabetic patients for ongoing insulin adjustments, identifies cancer in blood, and offers feedback to improve treatment success. This real-time capacity advances the objective of optimal care based on individual requirements by increasing the flexibility of individualized therapies. [51,59]

In recent years, nanotechnology and the development of nanoparticles have significantly transformed clinical practices by addressing the limitations of traditional therapies and enhancing drug delivery systems. Additionally, developments in nanosensors enable real-time monitoring of treatment responses and early disease identification, enabling dynamic therapy modifications based on patient measurements. Furthermore, these advancements facilitate pharmacogenomic testing, which allows medical professionals to tailor medication schedules based on genetic profiles, maximizing both safety and effectiveness. Given the circumstances, incorporating nanotechnology into personalized medicine not only improves therapeutic results but also opens the door to safer, more efficient treatment regimens catered to each patient's particular needs, transforming patient care. The potential for these technologies to enhance health outcomes keeps expanding as research advances but it also faces several limitations.

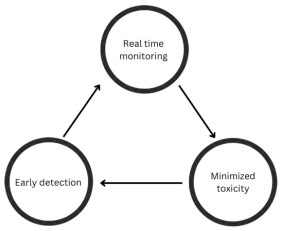


Figure 2: highlights the additional benefits of incorporating nanotechnology in personalized medicine.

While Nano particles (NP) have made strides in diagnostics and therapeutic applications—particularly in fields like oncology and genome engineering. This slower progress is partly due to the biological variability among patients; most NP platforms are screened in broad populations, where differences in patient biology can obscure therapeutic efficacy.

Additionally, the scarcity of stratified clinical trials makes it challenging to predict which NP platforms will be most effective, as stratified patient populations may respond more uniformly to treatment. Personalized NP designs also reduce the potential market size by limiting the number of eligible patients, which can raise financial risks due to the excessive costs of developing these advanced platforms. High development costs and a limited market thus pose challenges for the clinical translation and commercialization of NPs in personalized medicine, underscoring the need for optimized platforms and cost-effective approaches [51,54,56]

1.5 Stem cell

Stem cells are pluripotent cells, a type of cell that can develop into any type of cell in the body and can grow more than 200 types of cells. They are a group of undifferentiated, self-renewal cells arising from a single clonal cell. Advancements in stem cells have been contributing to the treatment of diseases which have no cure or treatment yet. Studies have shown and proven the use of stem cells in experimental research and cell therapies including hematological, skin regeneration heart diseases and disorders not only in humans but also in veterinary medicines. Stem cells are classified in different abilities, which include totipotent, pluripotent, multi potent or unipotent. This review discusses the recent developments involving stem cell therapies being used in advancements in personalized medicine. [60,61,62]

Stem cells are gaining importance in drug development, especially in modeling diseases, testing toxicity, and supporting regenerative therapies like tissue and organ repair.[63] Human-induced pluripotent stem cells (iPSCs) have significantly advanced stem cell research by being generated through the reprogramming of human skin cells. Scientists can develop patient-specific cells that resemble the features of different conditions by transforming adult cells into iPSCs. To investigate disease causes and find novel therapeutic targets, these iPSCs can be differentiated into certain cell types, such as neurons or cardiomyocytes. In complicated diseases where patient-specific treatment responses may be evaluated, such as Parkinson's, Amyotrophic lateral sclerosis, or cardiac diseases,

this method is especially helpful. The effective production of liver and pancreatic cells using the new method may speed up drug development and aid in the treatment of diabetes by improving disease models for individualized therapy. [64,65,66]

Additionally, stem cells are used to improve toxicity testing and medication screening. Because of genetic diversity, traditional drug testing frequently fails to predict the reactions of individual patients. To better anticipate negative effects, iPSCs can be created from a patient's cells and differentiated into liver or heart cells to assess how the patient metabolizes medications. This method lessens the possibility of negative side effects and aids in the creation of safer, effective drugs. [64,65]

There are several obstacles to overcome when implementing stem cell therapies in personalized medicine, especially with relation to the treatments' safety and scalability. The difficulty of producing stem cells is a significant barrier. The production procedure is expensive and time-consuming due to the necessity for specialized facilities and strict quality control. These elements hinder the quick development of scalable stem cell-based treatments by slowing the advancement through clinical trial phases. Extensive preclinical studies with animal models are necessary for this research, which raises the overall cost and regulatory obstacles.

Addressing these challenges will require coordinated efforts in research, regulatory reforms, and technological advancements to fully harness the potential of stem cells in personalized healthcare. [67,68]

Incorporating Technologies Together

The aim of this discussion is to analyze the effects of the previously mentioned technologies on the advancement of personalized medicine. We seek to evaluate how these technologies can work in collaboration to address present issues and accelerate the development of customized healthcare solutions by contrasting their efficacy, drawbacks, and synergies.

Personalized medication development uses innovative technologies—genetic sequencing, artificial intelligence, OoC, nanotechnology and stem cells—to transform healthcare. By customizing treatments to each patient's unique profile, these advancements allow for more effective and less harmful side effects through precise disease modeling, targeted therapy, and better drug delivery. AI speeds up data processing and improves forecast accuracy, while genomic insights inform treatment choices. Nanotechnology guarantees precise, effective medication delivery, and organ-on-chip models and stem cells mimic human physiology for improved drug testing.

Additionally, these technologies may be successfully combined to provide a more streamlined and effective drug development process. Organ-on-chip devices can more closely resemble human physiological responses by utilizing artificial intelligence (AI) to dynamically modify circumstances. AI, for example, could identify trends in OOC experiment data to forecast toxicity or efficacy, increasing the precision of early-stage drug evaluations. Additionally, AI-powered analytics can improve experimental designs, minimizing drug testing's trial-and-error phase and enabling customized medical strategies. [69,70,71]

In an equivalent manner AI can be incorporated with genomic sequencing. AI algorithms can sort through enormous volumes of genetic data to find patterns and mutations connected to illnesses more efficiently. As a result, more accurate and individualized therapy choices are made possible by the quicker detection of disease markers and possible therapeutic targets. AI also helps refine clinical decision-making by separating harmful from benign variants. AI speeds up the integration of genomics in healthcare by automating intricate genetic analysis, which lowers the time and expense involved in precision medicine. [72]

Personalized drug testing and disease modeling are made possible by stem cells producing patient-specific tissues that mimic organ functions in Organ-on-Chip (OOC) systems. This method increases the possibility for precision medicine by enabling more accurate, customized evaluations of therapy responses and by this way we can also incorporate stem cells in OoC system. [44]

Limitations

Even though personalized medicine has a lot of promise, there are several obstacles to overcome in its implementation across many technologies. These challenges frequently coexist, reflecting more general problems incorporating innovative medical advancements into standard clinical practice. Personalized treatments are expensive, which is the major obstacle. Advanced imaging, artificial intelligence tools, and bioinformatics platforms are all necessary for technologies like genome sequencing, stem cell therapies, and nanotechnology. The cost burden includes data management, storage, and analysis in addition to investing in this technology. Another significant issue is the quality and scarcity of data. Large datasets are crucial to personalized medicine's ability to pinpoint the genetic, environmental, and behavioral variables that affect illness and how well a treatment works. However, there are frequently gaps in our understanding of complicated diseases due to the restricted gathering of comprehensive and diverse datasets. [2,73,74,75] Healthcare practitioners' present level of competence is not keeping up with the rapid advancement of customized medicine technologies. Many experts are not trained to use AI tools, evaluate complex genetic data, or apply stem cell-based therapies. Because healthcare systems are ill-equipped to utilize these innovative diagnostic and treatment alternatives, this knowledge gap prevents the adoption of modern technologies and impacts the standard of patient care. The use of technologies like organ-on-a-chip systems and nanotechnology is made more difficult by patient biology variability. Customized organ models or nanoparticles must be made to fit the unique characteristics of each patient, which calls for a great deal of study, creation, and verification. Inconsistencies in therapeutic outcomes may result from this variability, particularly if the current models are mostly evaluated on general populations rather than stratified groups. All of these technologies present numerous ethical and legal issues. For example, the use of embryonic cells in stem cell therapies and the drawn-out regulatory approval procedures present serious ethical issues. In the same way, AI in healthcare must negotiate the challenges of patient permission, data bias, and the requirement for open algorithms. The ethical issues surrounding genetic privacy and the possibility of discrimination based on genetic predispositions are further complicated by genomic sequencing. A coordinated strategy incorporating regulatory changes, technology breakthroughs, and thorough training for healthcare professionals is needed to address these complex issues. [2,73,74,75] Figure 3 highlights the major challenges faced in the implementation of personalized medicine.



Figure 3

Conclusions

As the field advances, personalized healthcare is expected to become prevalent and more reliable with the enhancements in technology and therapeutics. The goal is to refine not only the efficiency of characterizing individuals but also further developments and validation of personalized medicines to demonstrate their effectiveness. This can be achieved by, introducing pharmacogenomics into clinical trials, anticipating efficient clinical trials based on a more thorough understanding of the genetic basis of disease and foreseeing some previously failed medications to be acknowledged as risk-free and potent, leading to their approval for specific subgroups of patients.

We have investigated each technology's transformational potential in this study to overcome the shortcomings of conventional medicine, enhance treatment efficacy, and minimize side effects. Although there are many advantages to integrating these technologies, the path to their complete acceptance is difficult, and overcoming these obstacles will require a team effort that involves constant study, creative thinking, and supporting legislation.

In conclusion, the ability to incorporate these technologies and capitalize on their advantages to provide a unified, patient-centered healthcare paradigm will determine the future of personalized medicine. We may bring in a new era of medicine that is more customized, preventative, and predictive by adopting this be integrated approach, which will eventually improve patient outcomes and quality of life.

Conflicts of Interest

No Conflicts of Interest.

References

1. Chan IS, Ginsburg GS. (2011) "Personalized medicine: progress and promise". *Annual review of genomics and human genetics*. Sep 22;12(1): pp217-44.
2. Goetz LH, Schork NJ. (2018) "Personalized medicine: motivation, challenges, and progress". *Fertility and sterility.* Jun 1;109(6): pp952-63.
3. Su J, Yang L, et al; (2024) "Personalized drug therapy: innovative concept guided with proteoformics". *Molecular & Cellular Proteomics*. Mar 1;23(3).
4. Mathur S, Sutton J. (2017) "Personalized medicine could transform healthcare". *Biomedical reports*. Jul 1;7(1): 3-5.
5. Khoury MJ, et al; (2020) "The intersection of genomics and big data with public health: opportunities for precision public health". *PLoS medicine*. Oct 29;17(10): e1003373.
6. Vashisht, V, et al; (2023). "Genomics for Emerging Pathogen Identification and Monitoring: Prospects and Obstacles". *BioMedInformatics*, *3*(4), 1145-1177.
7. Park ST, Kim J. (2016) "Trends in next-generation sequencing and a new era for whole genome sequencing". *International neurourology journal*. Nov;20(Suppl 2): S76.
8. Hess JF, Kohl TA, et al; (2020) "Library preparation for next generation sequencing: A review of automation strategies". *Biotechnology advances*. Jul 1;41: 107537.
9. Frese KS, et al; (2013) "Next-generation sequencing: from understanding biology to personalized medicine". *Biology*. Mar 1;2(1): 378-98.
10. Pareek CS, et al; (2011) "Sequencing technologies and genome sequencing". *Journal of applied genetics*. Nov;52: 413-35.
11. Barba E, et al; (2020) "Genome Informatics Pipelines and Genome Browsers". *InApplied Genomics and Public Health* Jan 1 (pp. 149-169).
12. Ginsburg GS, Willard HF. (2009) "Genomic and personalized medicine: foundations and applications". *Translational research*. Dec 1;154(6): pp277-87.
13. Breiman, L. (2001) "Random Forests". *Machine Learning* **45**, 5–32.
14. Guyon, I., Weston J, *et al.* (2002) "Gene Selection for Cancer Classification using Support Vector Machines". *Machine Learning* **46**, pp389–422.
15. Aerts, H. (1996). "Chitotriosidase-New biochemical marker". *Gauchers News*.
16. Alizadeh, A. et al. (2000). "Distinct types of diffuse large B-cell lymphoma identified by gene expression profiling". *Nature*, *403: 3*, pp503-511.
17. Alon, U. et al. (1999). "Broad patterns of gene expression revealed by clustering analysis of tumor and normal colon cancer tissues probed by oligonucleotide arrays". Cell Biology *PNAS*, *96*, pp6745-6750,.
18. Aronson, N. (1999). "Remodeling the mammary GI and at the termination of breast feeding: Role of a new regulator protein BRP39". The Beat, University of South Alabama College of Medecine, July, 1999.
19. Ben Hur, A., et al; (2000). "A support vector method for clustering". *Advances in Neural Information Processing Systems 13*, Cambridge, MA: MIT Press.
20. Askr H, (2023) "Deep learning in drug discovery: an integrative review and future challenges". *Artif Intell Rev*;56(7): 5975-6037.
21. Anil K. Jain, (2010) "Data clustering: 50 years beyond K-means, Pattern Recognition Letters", Volume 31, Issue 8, Pages 651-666, ISSN 0167-8655,
22. Arabi, A. A. (2021). "Artificial Intelligence in Drug Design: Algorithms, Applications, Challenges and Ethics". *Future Drug Discovery*, *3*(2).
23. Blanco-González A, (2023) "The Role of AI in Drug Discovery: Challenges, Opportunities, and Strategies". *Pharmaceuticals (Basel)*. Jun 18;16(6): 891.
24. Mouchlis VD, et al; (2021) "Advances in de Novo Drug Design: From Conventional to Machine Learning Methods". *Int J Mol Sci*. Feb 7;22(4): pp1676.
25. Baruffaldi S, et al; (2020) "Identifying and measuring developments in artificial intelligence". *Oecd Sci. Technol. Ind. Work. Pap*.
26. Wu H, Wang C, et al; (2017) "Interpreting shared deep learning models via explicable boundary trees". arXiv. 1709.03730

27. Zhao S, Talasila M, et al; (2018) "Packaging and Sharing Machine Learning Models via the Acumos ai Open Platform"; Proceedings of the 2018 17th IEEE International Conference on Machine Learning and Applications (ICMLA). [(accessed on 28 January 2021)]. pp. 841–846.

28. Tan J J, Cong XJ, et al; (2010) "Therapeutic strategies underpinning the development of novel techniques for the treatment of HIV infection". *Drug Discov*. Today.;15: pp186–197.

29. Hopkins A. (2021) "All Drugs Will be Designed by Computers by 2030". *The Telegraph*. [(accessed on 28 January)]

30. Zhavoronkov A,et al; (2019) "Deep learning enables rapid identification of potent DDR1 kinase inhibitors". *Nat. Biotechnol*;37: pp1038–1040.

31. Methods Mol Biol, Schork NJ. (2013) Artificial Intelligence and Personalized Medicine. *Cancer Treat Res*. 2019;178: 265-283.

32. Hamed Taherdoost, Alireza Ghofrani, (2024) "AI's role in revolutionizing personalized medicine by reshaping pharmacogenomics and drug therapy", *Intelligent Pharmacy*, Volume 2, Issue 5, Pages 643-650, ISSN 2949-866X

33. inyu Li, et al; (2024) "Machine learning based androgen receptor regulatory gene-related random forest survival model for precise treatment decision in prostate cancer", Heliyon, Volume 10, Issue 17, e37256, ISSN 2405-8440

34. jhe Huang, et al; (2024) "Theoretical insights into a turn-on fluorescence probe based on naphthalimide for peroxynitrite detection", Heliyon, Volume 10, Issue 17, e37298, ISSN 2405-8440

35. Vunjak-Novakovic G, et al; (2021) "Organs-on-a-chip models for biological research". Cell. Sep 2;184(18): pp4597-4611.

36. Toepke MW, and Beebe DJ (2006). "PDMS absorption of small molecules and consequences in microfluidic applications". Lab on a chip 6, 1484–1486.

37. Trapecar M, et al. (2020). "Gut-Liver Physiomimetics Reveal Paradoxical Modulation of IBD-Related Inflammation by Short-Chain Fatty Acids". *Cell systems* 10, 223–239.e229.

38. Vatine GD, et al. (2019). "Human iPSC-Derived Blood-Brain Barrier Chips Enable Disease Modeling and Personalized Medicine Applications". *Cell stem cell* 24, pp995–1005.e1006.

39. Vernetti L, et al. (2017). "Functional Coupling of Human Microphysiology Systems: Intestine, Liver, Kidney Proximal Tubule, Blood-Brain Barrier and Skeletal Muscle". Scientific reports 7, pp42296.

40. Viravaidya K, et al; (2004). "Development of a microscale cell culture analog to probe naphthalene toxicity". *Biotechnology progress* 20, pp316–323.

41. Wang G, McCain ML, et al. (2014). "Modeling the mitochondrial cardiomyopathy of Barth syndrome with induced pluripotent stem cell and heart-on-chip technologies". Nature medicine 20, pp616–623.

42. Wikswo JP, Curtis EL, et al; (2013). "Scaling and systems biology for integrating multiple organs-on-a-chip". Lab on a chip 13, pp3496–3511.

43. Leung C.M, *et al.* (2022) "A guide to the organ-on-a-chip". *Nat Rev Methods Primers* **2**, 33.

44. van den Berg A, (2019) "Personalised organs-on-chips: functional testing for precision medicine". Lab Chip. Jan 15;19(2): pp198-205.

45. Woodruff P. G., et al ; (2015). Lancet.; 385: pp1789–1798.

46. Friedman A. A., et al; (2015) "Flaherty K. T". *Nat. Rev. Cancer*.15: pp747–756.

47. Dekkers J. F, Wiegerinck C. L, de Jonge H. R, Bronsveld I, Janssens H. M, de W. Groot K. M, Brandsma A. M, de Jong N. W. M, Bijvelds M. J. C, Scholte B. J, Nieuwenhuis E. E. S, van den Brink S, Clevers H, van der Ent C. K, Middendorp S, Beekman J. M. Nat.

48. Danku AE, et al; (2022) "Organ-On-A-Chip: A Survey of Technical Results and Problems". *Front Bioeng Biotechnol*. Feb 10;10: 840674.

49. Wikswo J. P et al. (2013). "Scaling and Systems Biology for Integrating Multiple Organs-On-A-Chip". Lab Chip 13, 3496.

50. Sun W, et al. (2019). "Organ-on-a-Chip for Cancer and Immune Organs Modeling". *Adv. Healthc. Mater*. 8, 1801363. 10.1002/adhm.201801363

51. Mitchell M.J, *et al;* (2021) *"*Engineering precision nanoparticles for drug delivery". *Nat Rev Drug Discov* **20**, pp101–124.

52. Alghamdi MA, et al; (2022) "The Promise of Nanotechnology in Personalized Medicine". *J Pers Med*. Apr 22;12(5): 673.

53. Sun L, *et al.* (2023) "Smart nanoparticles for cancer therapy". *Sig Transduct Target Ther* **8**, 418.

54. Rosenblum D, *et al;* (2018) "Progress and challenges towards targeted delivery of cancer therapeutics". *Nat Commun* **9**, 1410.

55. Hassanin I, Elzoghby A. (2020) "Albumin-based nanoparticles: a promising strategy to overcome cancer drug resistance". *Cancer Drug Resist*. Nov 3;3(4): pp930-946.

56. Chawla R, et al; (2021) "Integrated Role of Nanotechnology and Pharmacogenetics in Diagnosis and Treatment of Diseases [Internet]". *Pharmacogenetics. IntechOpen*.

57. Xu J, Chen D, et al; (2021) "one step method for isolation of genomic DNA using multi-amino modified magnetic nanoparticles". RSC advances;11(6): pp3324-32.

58. Cheng MM, Cuda G, et al; (2006) "Nanotechnologies for biomolecular detection and medical diagnostics". *Current opinion in chemical biology*. Feb 1;10(1): pp11-9.

59. Alrushaid N, et al; (2023) "Nanotechnology in Cancer Diagnosis and Treatment". *Pharmaceutics*.;15(3): 1025.

60. Kolios G, (2013) "Introduction to Stem Cells and Regenerative Medicine". Respiration [Internet].;85(1): 3–10.

61. Rajabzadeh N, Fathi E, Farahzadi R.et al; (2019) "Stem cell-based regenerative medicine". Stem Cell Investigation [Internet]. Jul;6(19): pp19–9.

62. Ahmed M, et al; (2024) "Recent advancements in stem cell-based therapies". *Pure and Applied Biology*. Dec 1;13(4): pp464-82.

63. Wang XM, et al; (2012) "The gene expression profiles of induced pluripotent stem cells from individuals with childhood cerebral adrenoleukodystrophy are consistent with proposed mechanisms of pathogenesis". *Stem Cell Research & Therapy*. Oct 4; pp3(5)

64. Chun YS, et al; (2011) "Induced pluripotent stem cells and personalized medicine: current progress and future perspectives". Anatomy & cell biology. Dec 1;44(4): pp245-55.

65. Paik DT, et al; (2020) "Patient and disease–specific induced pluripotent stem cells for discovery of personalized cardiovascular drugs and therapeutics". *Pharmacological reviews*. Jan 1;72(1): pp320-42.

66. Arjmand B, et al; (2017) "Personalized regenerative medicine". *Acta Medica Iranica*. Mar 6: pp144-9.

67. Lightner AL, Chan T. (2021) "Precision regenerative medicine". *Stem Cell Research & Therapy*. Dec;12: 1-3.

68. Cinti C, et al; (2024) "The Roadmap toward Personalized Medicine: Challenges and Opportunities". *Journal of Personalized Medicine*. May 21;14(6): 546.

69. Deng S, Li C, et al; (2023) "Organ-on-a-chip meets artificial intelligence in drug evaluation". *Theranostics*.;13(13): 4526.

70. Baig MA. (2024) "Bridging the Gap: Integration of Artificial Intelligence with Organ-on-Chip (AI-OoC)". *IJLAI Transactions on Science and Engineering*. Jan 14;2(1): pp17-23.

71. Baig MA, Li S. "AI-powered Human-on-Chip: Redefining Biomedical Frontiers: Human-on-Chip".

72. Quazi S. (2022) "Artificial intelligence and machine learning in precision and genomic medicine". *Medical Oncology*. Jun 15;39(8): 120.

73. Yamamoto, Y, et al; (2022) "Current status, issues and future prospects of personalized medicine for each disease". *Journal of Personalized Medicine*, *12*(3), p.444

74. Hamburg M.A and Collins, F.S, (2010). "The path to personalized medicine". *New England Journal of Medicine*, *363*(4), pp.301-304.

75. Salari P, Larijani B. (2017) "Ethical Issues Surrounding Personalized Medicine: A Literature Review". *Acta Med Iran*.;55(3): pp209-217.