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A RIVIEW ON DIGITAL TWINS IN PERSONALIZED MEDICINE: A FUTURE IN PHARMA CARE

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ABSTRACT

Digital twin technology represents a transformative advancement in healthcare and pharmaceutical sciences. A digital twin is a dynamic virtual model of a patient, organ, or biological system that continuously integrates data from electronic health records, genomics, imaging, and wearable sensors. By combining artificial intelligence, machine learning, and Internet of Things (IoT) technologies, digital twins enable real-time simulations that can predict disease progression, optimize drug dosing, and support clinical decision-making. In personalized medicine, digital twins play a pivotal role in tailoring therapies to individual patient needs. Recent applications in cardiology, oncology, diabetes management, and pharmacogenomics demonstrate their ability to improve therapeutic outcomes while minimizing adverse drug reactions. Notably, digital twins have been explored in simulating treatment responses for drugs such as warfarin, insulin, cisplatin, and adalimumab, thereby ensuring safer and more precise dosing strategies. Beyond clinical applications, digital twins contribute to hospital operations, clinical trial design, and critical care management, making healthcare systems more predictive, preventive, and patient-centered. However, challenges remain regarding data privacy, ethical considerations, interoperability, and regulatory approval. Regulatory agencies such as the FDA and EMA are actively working toward establishing frameworks for the safe and effective integration of this technology. Overall, digital twins bridge the gap between computational modeling and real-world clinical practice. By enhancing precision medicine and pharmaceutical care, they hold the potential to revolutionize the future of healthcare, paving the way toward more efficient, individualized, and sustainable treatment strategies.

KEYWORDS: Digital Twin, Personalized Medicine, Drug Dosing, Pharmacogenomics, Artificial Intelligence, Pharma Care.

INTRODUCTION

In today's fast-growing world, everything is becoming smarter and more connected through technology. From shopping to studying, and from banking to healthcare, digital tools are helping people do things faster, easier, and more accurately. One of the most exciting digital innovations in healthcare is the concept of a Digital Twin, especially in the field of personalized medicine and pharma care. This technology has the power to change how doctors treat patients and how drugs are developed and tested.

Digital

The word "digital" simply means using computer technology to process, store, and share information. In a digital system, everything is converted into numbers (0s and 1s), which computers understand. Examples of digital things include mobile phones, computers, smart-watches, websites, and apps. In the medical field, digital systems include electronic health records, health apps, smart medical devices, and even robots used in surgery. "Digital" is the opposite of "manual" or "analogue" and brings speed, accuracy, and automation to our daily life.

Digital twins

A Digital Twin is a virtual copy of a real thing**,** like a person, organ, machine, or system. In medicine, it means a computerized version of a patient's body or a part of it (like a heart or brain). This digital copy is built using real data from medical tests, health monitors, lab reports, and wearable devices. It is not just a picture or model—it is a live, smart system that changes as your real body changes.

For example, if your blood sugar goes up, your digital twin will show that change. If you take a medicine, the twin can show how your body will react to it before you even take it. Doctors can use this twin to test different treatments, check for risks, and choose the safest and most effective option. This helps make medicine personalized, because it is designed to fit your body—not just the average patient.

Role of AI (Artificial intelligence)
Artificial Intelligence (AI) is the brain of the digital twin. AI is a smart computer system that can learn from data, think like humans, and make decisions. In healthcare, AI helps by:

1. Analysing huge amounts of patient data
2. Predicting disease before symptoms appear
3. Matching the right medicine to the right patient
4. Reducing medical errors
5. Improving treatment accuracy

Role of ChatGPT in Digital Twins
ChatGPT is a special type of AI created to understand and communicate in human language. It can answer questions, explain medical conditions, help patients understand their health reports, and assist doctors in interpreting results.

In digital twins, ChatGPT can play an important role such as.

1. Explaining complex health terms in simple words to patients
2. Generating patient reports using digital twin data
3. Communicating between doctors and patients through smart chat systems
4. Helping researchers by analysing scientific articles and creating summaries
5. Suggesting personalized health advice based on twin analysis

Real-World Example
Imagine you have heart problems. A doctor can create your heart's digital twin using your ECG reports, scans, and other data. They can then test different medicines on your twin to see how your real heart might respond. This way, they find the best medicine for you without putting your real heart at risk**.**

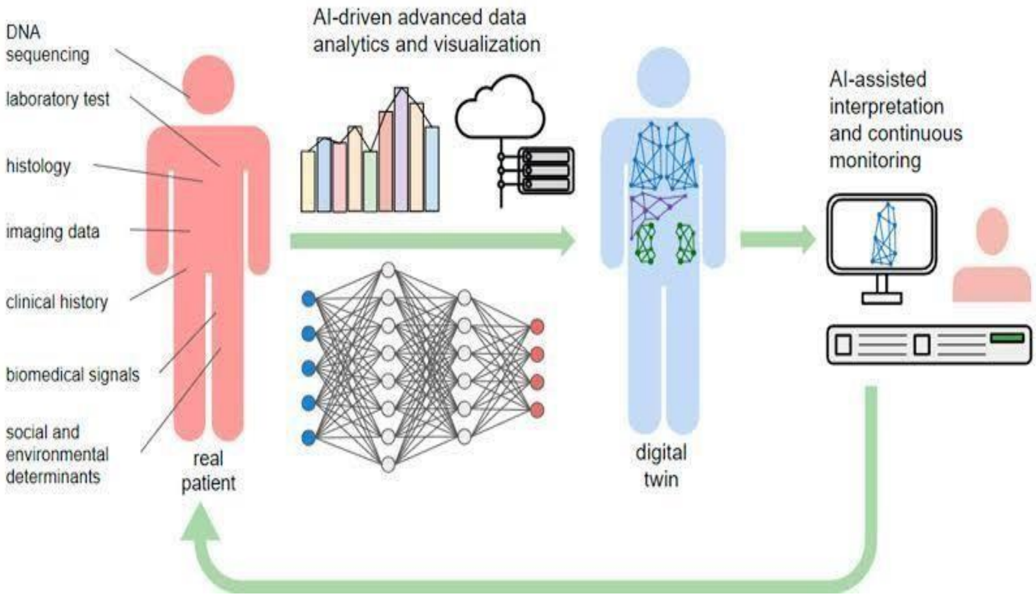


Figure 1:-Digital Twin Workflow for Patient Data and Treatment Simulation".

General Uses Of Digital Twins In Personalized Pharma Care
Digital twins are changing the way healthcare and pharmaceutical industries work. In simple words, a digital twin is a virtual copy of a real object, process, or even a person. In personalized pharma care, this virtual copy can represent a patient's body, organs, or disease patterns. By using this technology, doctors, researchers, and healthcare companies can test ideas, plan treatments, and predict results — without putting real patients at risk.

This section explains the general uses of digital twins in personalized medicine and pharma care, based on findings from multiple research articles.

Drug Development and Testing
Developing a new drug usually takes years of experiments and clinical trials. Digital twins can speed up this process by.

- Creating virtual patient groups for early drug testing
- Predicting side effects before human trials
- Testing different doses and treatment schedules in a safe, simulated environment

Example**:** Instead of testing a cancer drug directly on patients, researchers can first use digital twins of cancer cells and organs to see how the drug behaves.

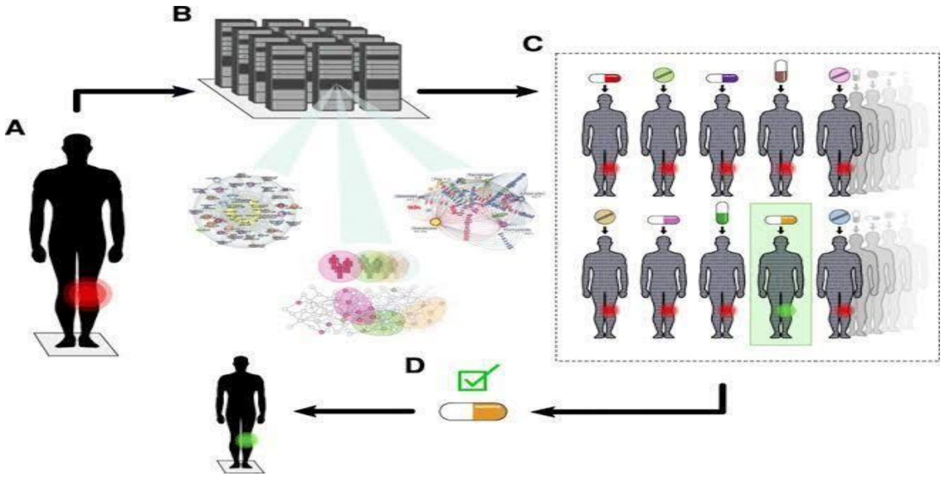


Figure 2: Virtual drug testing process — from lab data to patient twin simulation.

Chronic Disease Management
Chronic diseases like diabetes, heart disease, and asthma require continuous monitoring. Digital twins can:

- Track a patient's health in real time
- Predict possible health problems before they happen
- Suggest personalized changes in medicine or lifestyle

Example**:** A diabetes patient's digital twin can calculate the best insulin dose based on their diet, exercise, and daily blood sugar levels.

Surgery Planning and Simulation
Surgery can be risky, but digital twins make it safer by:

- Allowing surgeons to practice the operation in a virtual setting
- Predicting possible complications
- Customizing surgical steps for each patient

Example**:** A heart surgery can be simulated on a patient's digital twin so the surgeon knows exactly what to expect before the real operation.

Remote Patient Monitoring and Telemedicine
In rural areas or for patients who can't visit the hospital often, digital twins are very helpful.

- Doctors can monitor patients from far away
- AI can track health data and send alerts
- Patients can receive care without travelling

Example**:** An elderly patient with heart problems can be monitored 24/7, and any sudden changes will alert the doctor immediately.

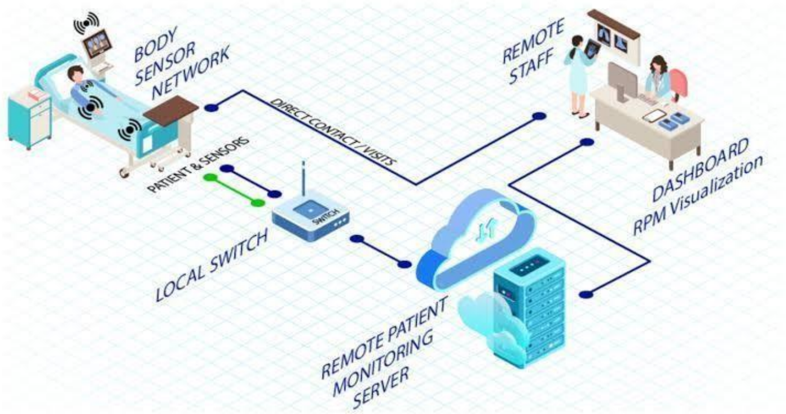


Figure 3: Remote monitoring setup with patient twin linked to hospital system.

Personalized Treatment Plans
Everyone's body reacts differently to treatment. Digital twins help by.

- Testing multiple treatment options on the virtual twin
- Finding the one that works best for that individual
- Adjusting the treatment over time as the patient changes

Table-1: How Digital Twins Improve Personalized Care.

STEP	USE	BENEFIT
Initial assessment	Create patient's twin	Accurate health profile
Treatment simulation	Test different therapies	Best-fit treatment found
Ongoing monitoring	Update twin with new health data	Dynamic and adaptive treatment

Public Health and Disease Outbreak Management

Digital twins can model entire cities or countries to see how diseases spread.

- Predicts the best ways to stop outbreaks
- Helps decide where to send medical resources
- Tests the effect of vaccination programs

Example: During COVID-19, digital twins could simulate how the virus spreads and test different lockdown strategies.

Medical Device Testing

Before a new medical device reaches patients, it must be tested. Digital twins can:

- Simulate device use in different patient conditions
- Identify design problems early
- Test long-term effects without waiting for years

Example: A pacemaker can be tested on a virtual heart before being used on real patients

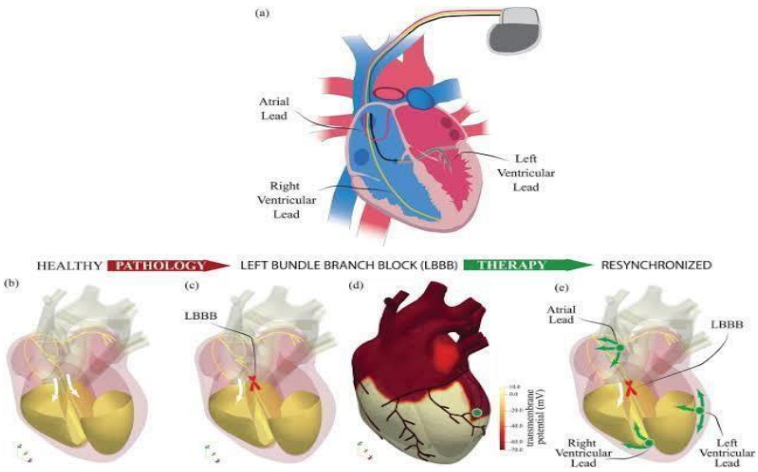


Figure 4: Pacemaker testing using a digital heart twin.

MECHANISMS AND MODEL

Introduction

The concept of digital twins is rooted in the idea that every physical entity — whether a machine, an organ, or a full human body — can be represented virtually in a dynamic model. In personalized medicine, this means that each patient has a unique digital replica that behaves like their real self. Unlike traditional medical records, which are static, a digital twin is continuously updated with new health data, making it a living and evolving copy.

In the pharmaceutical industry, mechanisms and models of digital twins are particularly important because they allow researchers and clinicians to understand how drugs interact with the human body, to predict therapy outcomes, and to design personalized treatment strategies. Mechanisms describe the step-by-step processes by which digital twins operate, while models describe the representations of biological systems that power those mechanisms. Together, they form the backbone of digital health innovation.

Mechanism of Digital Twins in Pharma Care

The mechanism of a digital twin in personalized medicine can be explained as a cyclical, continuous-loop process. This process is not linear but dynamic, meaning that with every cycle, the digital twin becomes smarter and more accurate.

Step 1: Data Collection

- Patient data is the foundation of a digital twin.
- Sources include:
  - o Electronic Health Records (EHRs): patient history, lab reports, prescriptions.
  - o Wearables & IoT Devices: heart rate monitors, blood glucose sensors, smart-watches.
  - o Medical Imaging: MRI, CT scans, ultrasound.
  - o Genomics & Proteomics: DNA sequencing, protein expression.
- Example: A diabetic patient's glucose levels from a continuous glucose monitor are fed into the twin in real time.

Step 2: Data Processing and Integration

- Raw data must be organized, cleaned, and standardized.
- Machine learning algorithms are applied to remove noise and ensure accuracy.
- Advanced data integration platforms combine structured (e.g., lab test values) and unstructured (e.g.,

doctor's notes) data.

Step 3: Model Construction

- Using the processed data, a virtual model of the patient is created.
- This model could be organ-specific (e.g., a heart twin), disease-specific (e.g., a cancer twin), or a full-body twin.
- The model is represented through mathematics, biology, and computer science.

Step 4: Simulation and Prediction

- Doctors and researchers can apply different therapies to the twin and observe simulated outcomes.
- Example: A twin of a cancer patient can be used to test various chemotherapy regimens to predict which one would be most effective with the least side effects.

Step 5: Clinical Decision and Feedback

- The simulation results are communicated to physicians.
- Once a therapy is given to the patient, the patient's real-world outcomes are fed back into the twin.
- This cycle continuously improves accuracy.

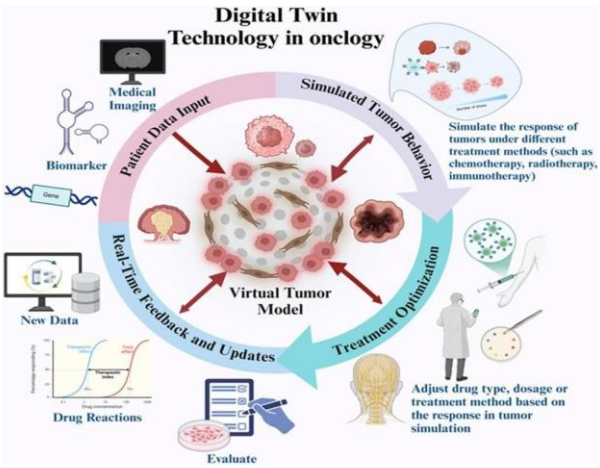


Figure 5: Closed-Loop Digital Twin for Personalized Therapy.

Types of Models Used in Digital Twins

Digital twins rely on multiple types of models, each serving a different purpose.

1. Mathematical Models

○ Built using equations that describe physiological processes.

○ Example: Pharmacokinetic (PK) models predict how drugs are absorbed, distributed, metabolized, and excreted.

○ Benefit: Highly accurate for drug-level predictions.

2. Biophysical Models

○ Represent the structure and function of organs.

○ Example: A digital lung twin that simulates airflow and gas exchange.

○ Benefit: Helps test ventilator settings or drug effects on breathing.

3. AI-Based Models

○ Machine learning models trained on large patient datasets.

○ Example: Predicting whether a breast cancer patient will respond to chemotherapy.

○ Benefit: Finds hidden patterns not visible to doctors.

Hybrid Models

○ Combine mathematical and AI-based approaches.

○ Example: A hybrid cancer twin that uses both tumor biology equations and AI imaging analysis.

○ Benefit: Provides a more holistic and reliable model.

Table-2: Comparison of Models Used in Digital Twin.

MODEL TYPE	KEY FEATURES	EXAMPLE APPLICATION
Mathematical.	Equation-based	PK/PD drug modeling
Biophysical	Organ structure simulation	Digital lung for ventilator use
AI-Based	Data-driven prediction	Drug response in oncology
Hybrid AI +	biological knowledge	Personalized therapy planning

Mechanism of Action (MOA) Simulation in Digital Twins

One of the most powerful applications of digital twins in pharma is simulating the mechanism of action (MOA) of drugs. Instead of testing on animals or patients, scientists can use twins to visualize the entire drug pathway.

Key Stages in MOA Simulation.

1. Drug–Receptor Binding
   - o The twin predicts binding affinity and strength between a drug and its receptor.
   - o Example: How an antihypertensive drug binds to ACE receptors.
2. Pathway Modeling
   - o Simulation of intracellular pathways affected by the drug.
   - o Example: Insulin pathway modeling in diabetes management.
3. Tissue-Level Response
   - o Prediction of how tissues or organs react.
   - o Example: Simulating liver metabolism of painkillers.
4. Therapeutic Effect
   - o Expected clinical outcome is measured virtually.
   - o Example: Reduction in tumor size.
5. Safety and Toxicity
   - o Side effects like kidney toxicity or cardiac risks are predicted before the real trial

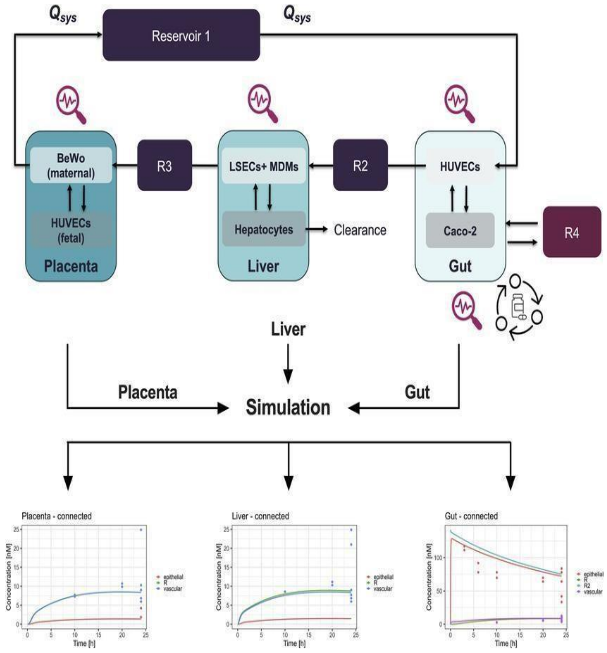


Figure 6: Digital Twin MOA Cycle for Pharmacokinetic Modeling.

Simulation Models in Clinical Applications

Simulation is one of the greatest strengths of digital twins in healthcare.

- Virtual Clinical Trials
  - o Digital twins represent thousands of patients, replacing part of large-scale trials.
  - o Saves billions of dollars and reduces ethical issues of human testing.
- Drug Dosage Optimization
  - o Different doses are virtually tested on a patient twin.
  - o Helps avoid underdosing (ineffective therapy) or overdosing (toxic effects).
- Organ-Specific Simulation
  - o Digital heart twins used for pacemaker design and arrhythmia treatment.
  - o Lung twins used during COVID-19 for ventilator setting optimization.
- Chronic Disease Simulation
  - o Simulates progression of long-term illnesses like hypertension, diabetes, or arthritis.
  - o Helps doctors design 5–10 year therapy plans for patients.

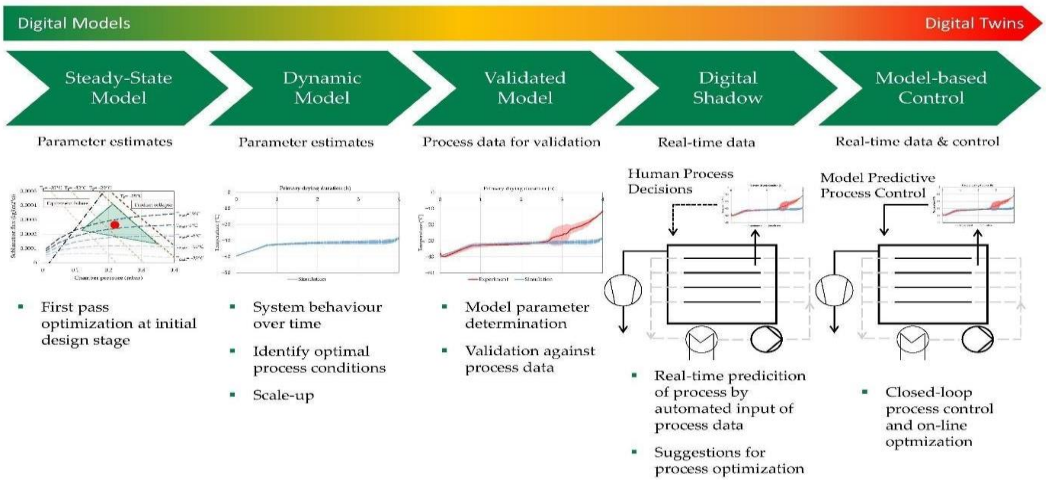


Figure 7: Simulation Framework for Dose Optimization.

APPLICATIONS OF DIGITAL TWINS IN PHARMA CARE

1. Digital Twins in Drug and Vaccine Development

Digital twins are now becoming very useful in how new medicines and vaccines are created. Normally, it takes many years and a lot of money to develop a single drug. Many times, even after spending so much effort, the drug fails in the final stage because it does not work as expected in real patients. Digital twins help to reduce this risk.

A digital twin of the human body or of a particular organ **(**for example, the liver or the heart) can be built using patient data, lab experiments, and computer models. Once this virtual model is ready, scientists can “test” new medicines on the twin before testing them on humans. If the medicine shows problems like side effects or toxicity in the twin, researchers can stop early and save cost.

In vaccines, digital twins can also help. They can simulate how the immune system will respond to a particular antigen. This means the best candidates for vaccines can be chosen faster, without wasting time on weak options. This reduces the failure rate and makes vaccine discovery much faster and safer.

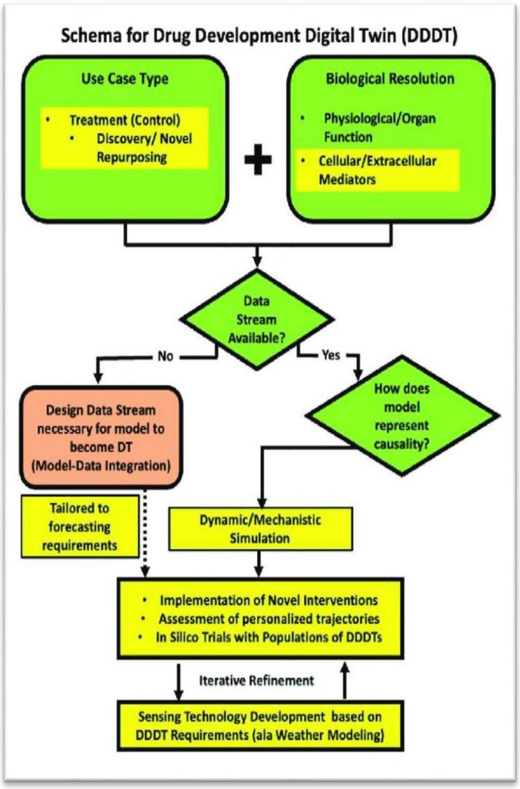


Figure 8: Workflow of Developing and Applying Medical Digital Twins for Drug Discovery, Testing, and Repurposing.

2. Digital Twins in Clinical Trials

Clinical trials are the most expensive and time-consuming part of drug development. It often takes thousands of volunteers and many years to test a medicine. Digital twins can solve this by creating "virtual patients."

For example, a digital twin can be made for a population of people with diabetes. Different medicines can then be tested on this virtual group before testing in real patients. This is called an "in silico trial." It reduces the number of real volunteers needed and also predicts which group of patients will benefit most.

Companies like Pfizer and AstraZeneca have already reported saving hundreds of millions of dollars by using digital twins and synthetic data in clinical trials. For rare diseases where it is difficult to find enough volunteers, digital twins are especially useful because a virtual control group can replace or reduce the real one.

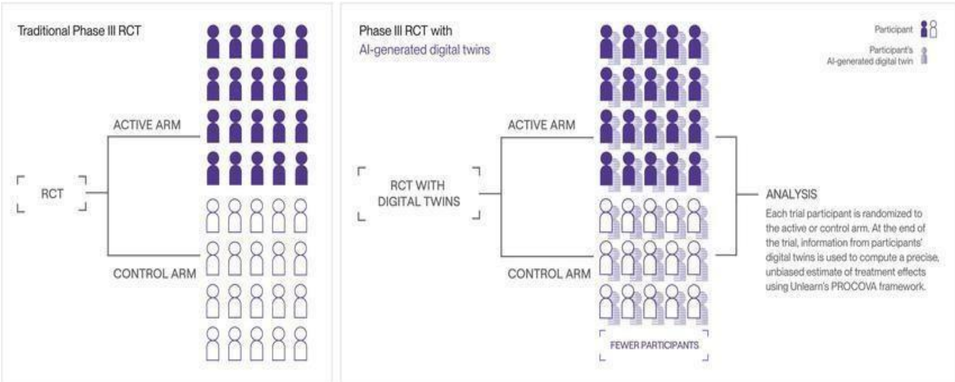


Figure 9: Comparison diagram of traditional trial (real patients only) vs. digital twin trial (virtual patients + real patients).

3. Personalized Medicine and Preventive Care

One of the most exciting uses of digital twins is in personalized medicine**.** Every person is different, and the same drug may work differently for two people. Digital twins can solve this by creating a "twin" of an individual patient using their genetics, age, lifestyle, medical history, and even data from wearable devices.

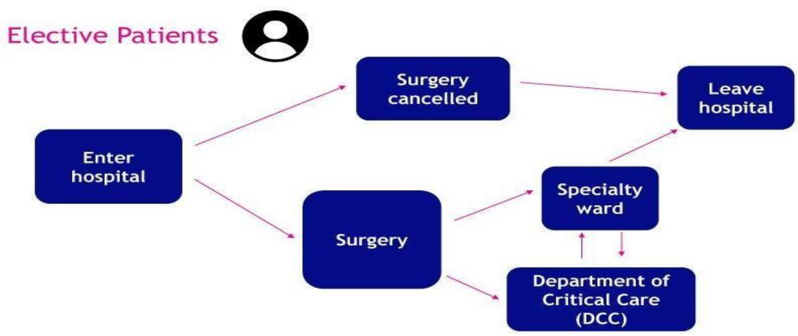
Doctors can then test different medicines or dosages on the twin to see what works best, without putting the real patient at risk. For example, in cancer treatment, digital twins can predict how a tumor will respond to chemotherapy and suggest the best dose. In heart diseases, they can model how a surgery or a pacemaker will affect the patient before it is actually done.

This approach does not only treat illness but also helps in prevention. By continuously monitoring the twin, doctors can detect problems early and give advice before the disease becomes serious.

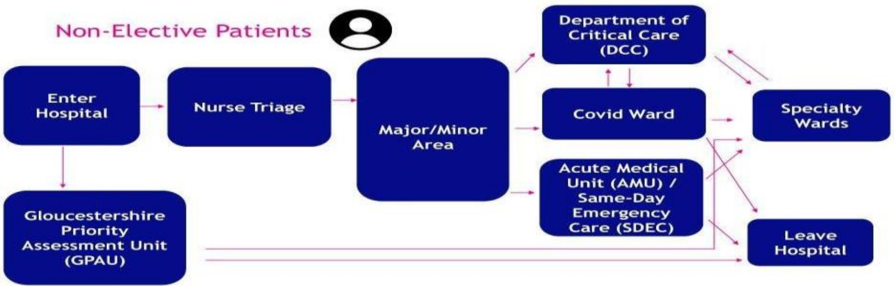
4. Digital Twins in Hospitals and Diagnostics

Hospitals are also using digital twins to improve their daily work. A digital twin of the hospital can show how patients move through emergency rooms, ICU, and wards. By running simulations, managers can understand problems like shortage of beds, staff, or equipment, and fix them in advance. This makes hospital operations more efficient and improves patient care.

Digital twins are also used in diagnostics and prosthetics**.** For example, before making an artificial limb, doctors can design a twin model of the limb to check the size, strength, and movement. This ensures that when the real limb is made, it fits perfectly, saving both time and cost.



Elective patient pathway reflected in the hospital digital twins:-Elective patients follow planned pathways for scheduled treatments, starting with pre-admission consultation, diagnostics, treatment or surgery, recovery, and discharge. Hospitals can plan bed allocation and equipment use in advance for these patients.



Non - Elective patient pathway reflected in the hospital digital twins :-Non- elective patients arrive unexpectedly through emergency or urgent referrals, requiring triage, rapid diagnostics, immediate treatment, and flexible bed and equipment management to handle sudden demand efficiently.

Figure 10: Diagram of hospital twin – showing patient flow, equipment use, and bed management.

USES OF DIGITAL TWINS IN PHARMACY

a. Drug Development and Optimization

- DTs simulate how drugs interact with human physiology.
- Virtual patient models help predict absorption, metabolism, distribution, and excretion of drugs.
- Enables faster drug development and reduces reliance on animal testing.

Table 4: Benefits of Digital Twins in Drug Development.

Stage	Traditional Approach	With Digital Twin
Preclinical	Animal studies, slow	Virtual human models, faster
Clinical Trials	Large patient groups	Simulated cohorts, reduced cost
Post-Market	ADR detected late	Continuous patient monitoring

b. Personalized Medicine and Dosing

- DTs allow pharmacists to customize drug doses based on patient-specific factors like genetics, age, weight, and comorbidities.
- Organs such as the liver and kidney can be modeled to predict drug metabolism and clearance, reducing adverse effects.
- Example: DTs guide anticoagulant therapy by predicting bleeding or clotting risks for individual patients.

c. Hospital Pharmacy Operations

- DTs optimize drug inventory, storage, and dispensing.
- IoT integration allows real-time monitoring of stock levels, temperature, and humidity.
- Predicts drug shortages and prevents wastage of expired medicines.

Table 5: Hospital Pharmacy Applications of Digital Twins.

AREA	TRADITIONAL	WITH DIGITAL TWIN
Inventory	Manual checking	Automated IoT tracking
Storage	Risk of spoilage	Real-time environment monitoring
ADR Reporting	Paper-based, delayed	Predictive analytics and alerts

d. Education and Training in Pharmacy

- DT simulations help pharmacy students and professionals practice dispensing and monitoring safely
- Allows simulation of rare ADRs and complex dosing scenarios without risk to patients.
- Improves decision-making skills for clinical pharmacists.

e. Mechanism of Digital Twins in Pharmacy

1. Data Collection: Patient records, lab reports, pharmacy inventory, IoT sensors.
2. Modeling: AI algorithms generate virtual replicas of patients or pharmacy systems.
3. Simulation: Test drug effects, interactions, and inventory processes virtually.
4. Feedback: Apply results to real-world treatment, dosing, and pharmacy management.

LATEST USES OF AI IN PHARMACY

Artificial Intelligence (AI) is transforming pharmacy by making processes faster, safer, and more efficient. It helps pharmacists analyze large amounts of data quickly, predict patient responses, and reduce errors. AI applications range from drug discoverytopatient monitoring and even pharmacy education. By using AI, pharmacists can provide personalized care**,** optimize workflows, and ensure patients take medicines correctly.

AI is particularly important because it can identify potential problems before they happen, such as adverse drug reactions or incorrect doses, saving both time and lives.

f. AI in Drug Discovery and Development

Developing new drugs is traditionally time-consuming and expensive. AI changes this by:

- Analyzing chemical compounds quickly to predict which could become effective drugs.
- Simulating how drugs interact with organs or cells without needing initial lab tests on animals.
- Detecting possible side effects or risks before clinical trials begin.
- Optimizing clinical trials by identifying suitable patient groups and predicting outcomes.

Example**:** During recent viral outbreaks, AI helped predict potential antiviral compounds, shortening research time by months.
This makes the drug development process more efficient, while also improving patient safety and reducing trial errors.

g. Personalized Medicine and Patient Care
AI allows pharmacists to tailor treatments to individual patients. Each patient's body is unique, so a medicine that works for one person may not work for another. AI can:

- Suggest optimal drugs and doses based on age, weight, genetics, and health conditions.
- Predict side effects before giving medication.
- Monitor chronic conditions like diabetes, heart disease, or kidney problems, adjusting treatments in real

Example: Two patients with high blood pressure may need different doses of the same drug. AI predicts how each patient's body will respond and recommends the safest, most effective dose.

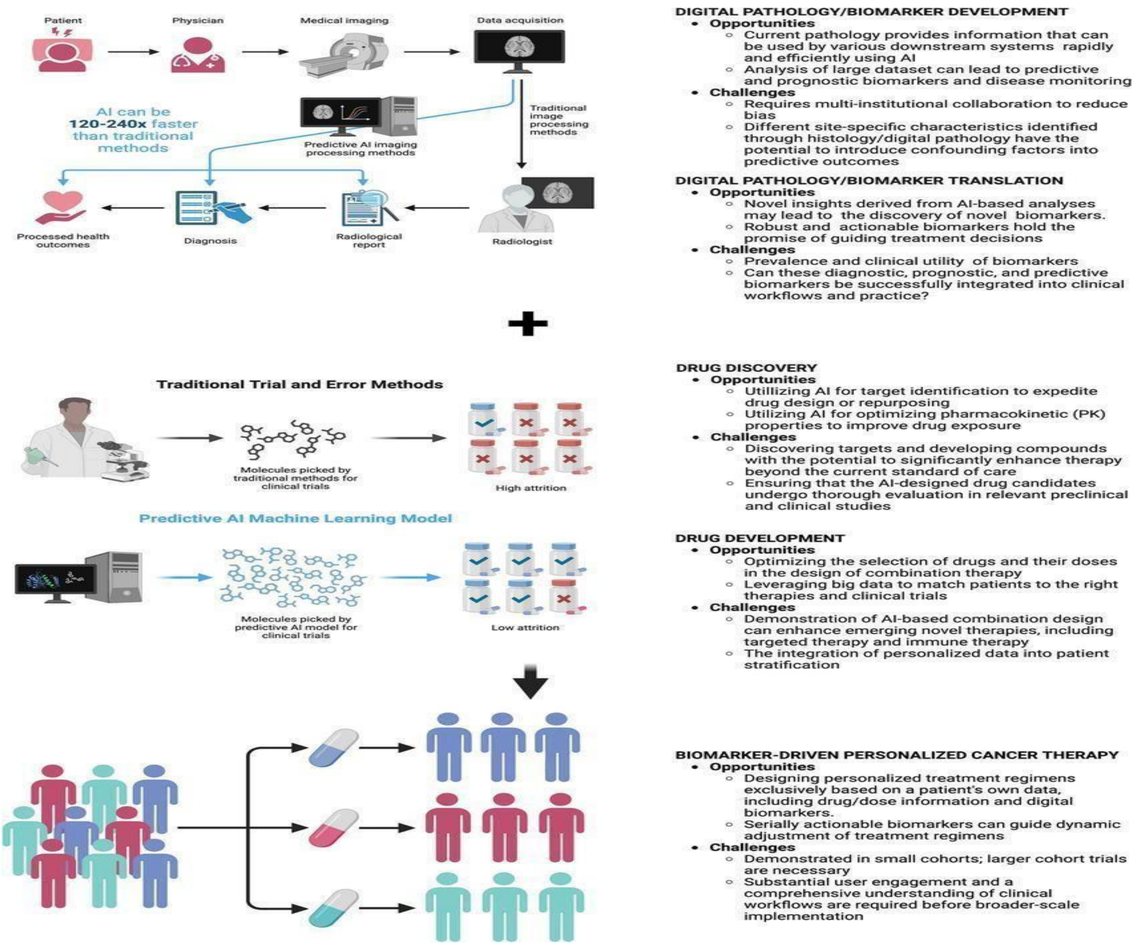


Figure 13: Artificial Intelligence–Enabled Digital Twin Models of Key Organs for Personalized Drug Dosing and Treatment Optimization.

h. Pharmacy Operations and Management
AI improves how pharmacies operate, making them more accurate and efficient. It helps with:

- Inventory management: Predicts which medicines will be needed, avoiding shortages or waste.
- Automated dispensing:Robots, guided by AI, prepare and dispense medicines quickly and accurately.
- Workflow optimization: AI analyzes pharmacy usage patterns, helping pharmacists organize stock and reduce delays.

Example**:** Hospitals now use AI to track medication use in real time, preventing shortages and ensuring critical drugs are always available.

i. Medication Adherence and Monitoring
Ensuring patients take medications correctly is crucial. AI helps by:

- Using smart pillboxes and apps that remind patients when to take their medicines.
- Monitoring doses and alerting patients or caregivers

if a dose is missed.

- Collecting data to help pharmacists adjust treatment plans.

Example**:** Diabetic patients use AI apps to track insulin doses and blood sugar levels, which helps maintain healthy glucose levels and prevents complications.

❖ Drug Safety and Pharmacovigilance

AI enhances patient safety by monitoring and predicting risks.

- Scans patient records, lab reports, and prescriptions to identify potential adverse drug reactions (ADRs).
- Predicts drug–drug interactions**,** avoiding harmful combinations.
- Detects patterns of misuse, like opioid overuse, to prevent serious health issues.

Example**:** AI can alert pharmacists if a patient might react negatively to a prescribed painkiller, suggesting safer alternatives.

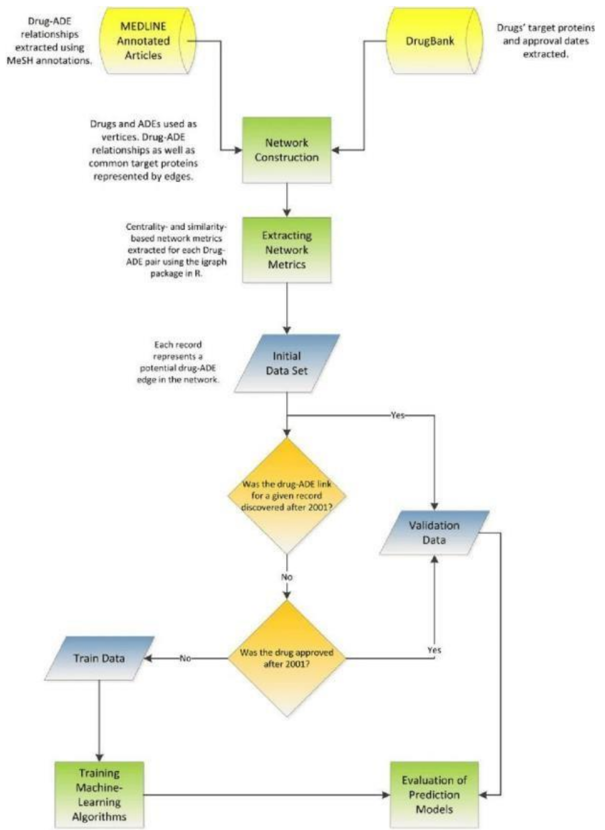


Figure 14: AI in Drug Safety and Pharmacovigilance.

j. AI in Pharmacy Education and Specialty Care

- Pharmacy students can use AI simulations to practice dispensing, monitoring, and problem-solving safely.
- Virtual patient models allow practicing rare drug reactions or complex dosing scenarios.
- Specialty care pharmacies use AI to develop personalized therapy plansfor patients with complex conditions, ensuring safer and more effective treatment.

Example**:** Oncology pharmacists use AI to predict how patients will respond to chemotherapy and adjust doses accordingly.

FUTURE OF DIGITAL TWINS IN AI WITH DRUG DOSE EXAMPLES

Digital Twins Work in Drug Dosing

The concept of a digital twin works like a flight simulator for medicine**.** Just like a pilot trains in a simulator before flying a real plane, doctors can test drug doses on a patient's virtual twin before giving them in real life.

Step-by-step process.

1. Collect Patient Data – Includes blood test results, genetic profile, organ function (liver, kidney, heart), blood pressure, glucose levels, and lifestyle habits.
2. Build a Digital Twin – AI uses this data to create a digital patient that behaves like the real one.
3. Simulate Different Doses – Multiple drug doses are tested on the twin.
4. Predict Effects – AI predicts which dose will be effective and safe, and which may cause side effects.
5. Prescribe Best Dose – Doctors select the safest, most effective option for the real patient.
6. Continuous Monitoring – As the patient's condition changes, the twin updates itself and adjusts the dose in real time.

- This avoids risky trial-and-error treatment and ensures each patient gets a dose that matches their body.

Examples of Drugs Where Digital Twins Help

Digital twins are especially useful for drugs that:

- Have a narrow therapeutic window **(**small difference between effective and harmful dose).
- Are life-saving but risky (like chemotherapy).
- Need continuous dose adjustment (like insulin). Here are some important examples with dose amounts.

1. Warfarin (Blood Thinner)
   - Usual dose: 2–10 mg/day
   - Problem: Too much causes dangerous bleeding**,** too little causes clots**.**
   - Twin role: Simulates blood clotting (INR) and finds the exact safe dose.
2. Insulin (Diabetes Medicine)
   - Usual dose**:** 0.3–1.0 units/kg/day
   - Problem: Wrong dose may lead to hypoglycemia (low sugar) or hyperglycemia (high sugar)**.**
   - Twin role: Connects to glucose sensors and adjusts insulin dose in real time.
3. Cisplatin (Cancer Chemotherapy)
   - Usual dose: 50–100 mg/m² IV every 3–4 weeks
   - Problem: High doses can damage kidneys**.**
   - Twin role: Predicts kidney safety and suggests safe lower dose if needed.
   - Adalimumab (Arthritis/Autoimmune Drug)
   - Usual dose: 40 mg injection every 2 weeks
   - Problem: Some patients respond slowly, while others respond too strongly.
   - Twin role: Predicts immune system response and adjusts schedule.
4. Carbamazepine (Epilepsy Drug)

o Usual dose: 200–1200 mg/day
o Problem: In some genetic types, standard doses cause severe skin reactions**.**
o Twin role: simulates metabolism and avoids unsafe doses.

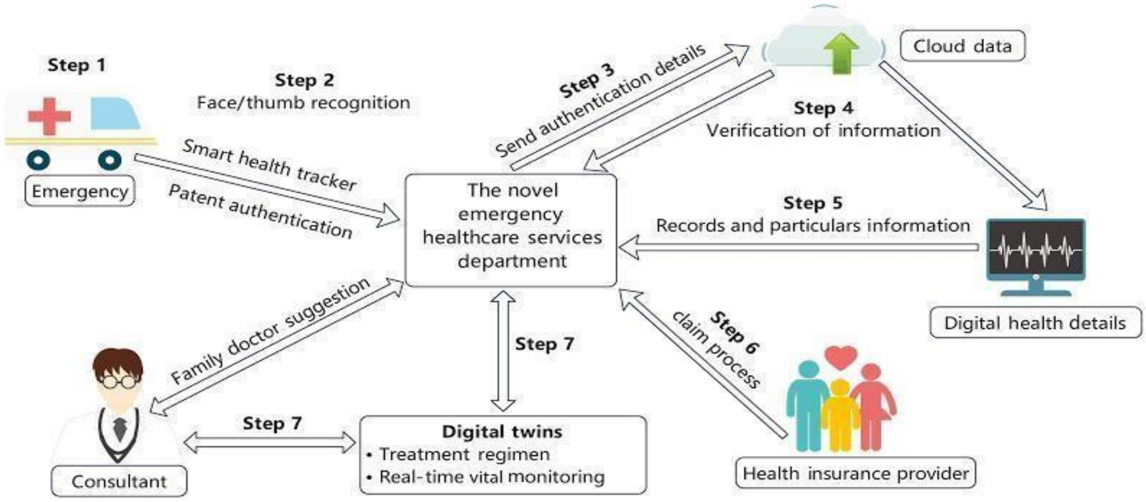


Figure 17: Digital Twin Applications in Different Drugs.

Benefits of Digital Twins in Drug Therapy
1. Right Dose for Each Patient – No more trial-and-error prescribing.
2. Fewer Side Effects – Risks are predicted before real treatment.
3. Continuous Personalization – Dose adjusts automatically with health changes.
4. Better Control of Chronic Diseases – Such as diabetes, hypertension, and arthritis.
5. Safer Use of Strong Drugs– Especially in cancer and heart patients.
6. Faster Drug Development– Twins can also be used in clinical trials to predict outcomes.

Future Outlook
In the next 10–15 years, digital twins will become a standard hospital tool**.** Doctors will be able to create a twin of every patient and test drugs virtually before prescribing. This will.
- Reduce hospital admissions due to adverse drug reactions**.**
- Improve patient safety for high-risk drugs.
- Save costs by preventing wasted treatments.
- Speed up the approval of new medicines.

Eventually, every patient may carry their own digital twin on a health card or smartphone app, which updates in real time and guides doctors about the safest treatment.

CONCLUSION
Digital twin technology, powered by artificial intelligence (AI), is changing the way healthcare is provided. It creates a virtual copy of a patient using their medical history, genetics, lifestyle, and real-time health data. Doctors and pharmacists can use this virtual model to test treatments, predict how the patient will respond, and choose the best therapy safely. This moves healthcare from a “one-size-fits-all” approach to care that is personalized for each patient. Digital twins are useful at every stage of medicine and pharmacy. In drug discovery, they can show how molecules interact and find possible side effects. This helps q0researchers choose the best drug candidates faster and at lower cost. In clinical trials, virtual patients can reduce the number of volunteers needed, making studies quicker and cheaper.

For patients with long-term or chronic illnesses, digital twins help doctors monitor health continuously. They can adjust treatments automatically if the patient’s condition changes. This helps make care safer, more effective, and easier for patients to follow.

In pharmacy practice, digital twins improve drug dosing, track side effects, and simulate hospital workflows. They also help manage medicine supply, predicting needs and preventing shortages. All these benefits make healthcare faster, safer, and more efficient.

Even with these advantages, digital twins have challenges. Making accurate virtual copies needs a lot of high-quality data. Privacy and cybersecurity are very important, and patients must agree to share their information. Also, there are no global standards for digital twins, so hospitals may find it hard to share models. Regulatory rules like those from FDA and EMA are still being developed for AI-driven healthcare.

Digital twins also support education and training for healthcare professionals. Medical students and new doctors can use virtual patients to practice decision-making without any risk to real patients. Hospitals can simulate complex cases and test new treatment strategies safely.

Another benefit is improving patient engagement. Patients can see their virtual twin and understand how treatments affect them. This helps them follow medical advice better and stay more involved in their own care. Digital twins can also reduce healthcare costs in the long term. By preventing adverse reactions, improving treatment success, and optimizing hospital resources, hospitals can save money while improving outcomes.

In the future, digital twins will become more accurate and easier to use. Advances in AI, wearable devices, and genomics will make them more precise. Hospitals may use digital twins as standard tools for diagnosis, personalized dosing, and preventive care. Patients may even carry their own digital twin in a smart health record for real-time guidance.

In conclusion, digital twins are a big step toward personalized medicine. They help doctors give the right treatment at the right time, reduce side effects, and make healthcare safer and more efficient. Although there are challenges, the benefits are much greater. With more research and adoption, digital twins are set to change the future of pharmacy and medicine.

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