Digital Twins in Healthcare

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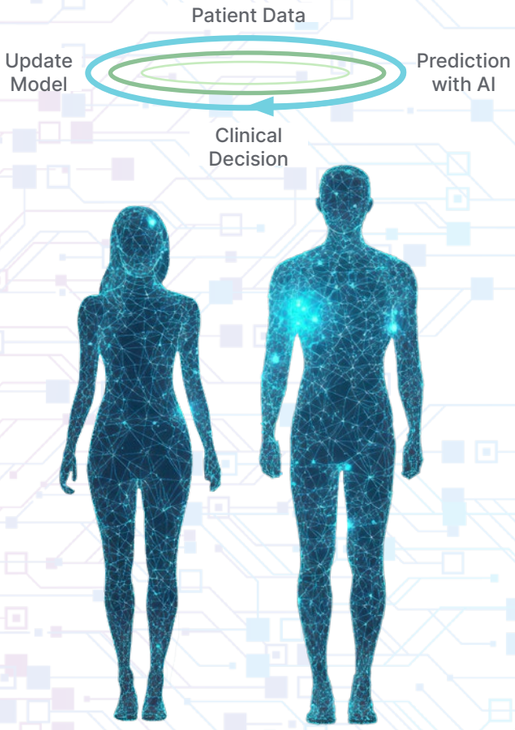
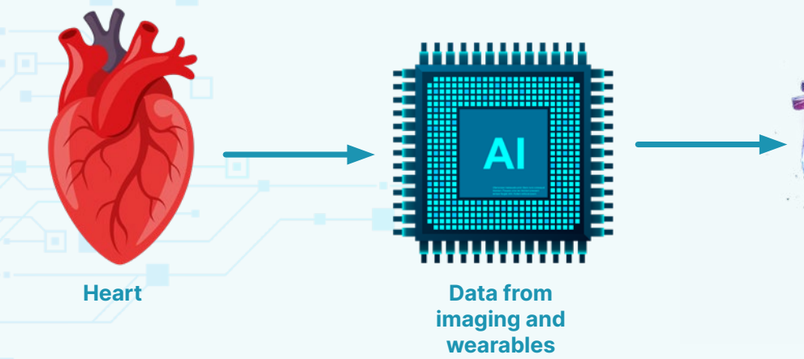
What are Digital Twins?

- Digital twins are computational replicas of organs, whole patients, or populations, used to enhance clinical decision making.[1]
- They integrate data to create personalised simulations.[1,2]
  - **Organ replicas:** mechanistic, patient-specific models that simulate organ function or physiology.
  - **Disease-specific predictions:** data-driven predictive models that forecast patient outcomes.
  - **Digital patients:** integrated whole-patient models combining clinical records, genomics, lifestyle, and real-time physiological data.
- By exchanging data between real and virtual twins, AI models can analyse health and predict patient outcomes.[1]



Emerging Applications

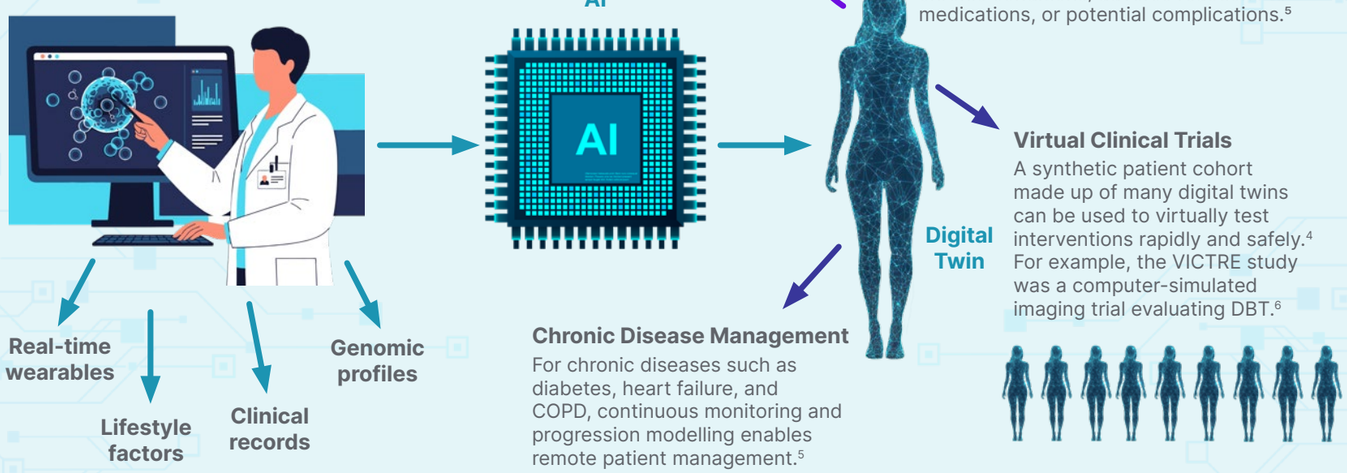
Organ Twins and Data-Driven Predictive Models



Medical Device and Drug Optimisation
Organ twins can predict how mechanical medical devices will perform, and mimick potential biochemical reactions and dose optimisation.[1] For example, the SIMULIA Living Heart model examines *in silico* organ drug interactions.[3]

Surgical Planning
In surgery, clinicians can rehearse procedures virtually to improve safety and outcomes.[1]

The Digital Patient



Precision Medicine
Digital twins help customise therapeutic intervention based on clinical history, lifestyle, genetics, and real-time physiology.[4] With AI, this can be used to detect early signs of risks, such as the development of chronic conditions, adverse reactions to medications, or potential complications.[5]

Virtual Clinical Trials
A synthetic patient cohort made up of many digital twins can be used to virtually test interventions rapidly and safely.[4] For example, the VICTRE study was a computer-simulated imaging trial evaluating DBT.[6]

Chronic Disease Management
For chronic diseases such as diabetes, heart failure, and COPD, continuous monitoring and progression modelling enables remote patient management.[5]

Ethical and Operational Barriers

Many applications remain at the proof-of-concept stage, requiring more research, data standardisation, and validation for clinical adoption.[2]

Consent and Compliance
Ethical challenges include maintaining ongoing informed consent as digital twins evolve, and ensuring GDPR/HIPAA compliance.[4]

Data Privacy
Patient privacy demands strong safeguards, including encryption, secure storage, and protection against unauthorised access.[1]

Interoperability
Limited interoperability across imaging and EHR systems highlights the need for standardised data formats.[1]

Addressing Bias
Bias risks emerge when datasets overrepresent certain demographics; addressing this through robust governance, validation, and subgroup-specific validation of digital twin models is essential.[7]

Regulatory Considerations
Adherence to established verification, validation, and credibility frameworks, including FDA and EMA guidance, is essential to ensure the clinical credibility of digital twin approaches.[8]

Forecasting the Future of Digital Twins

Anticipated Benefits[1,4]

- Lower costs of trials.
- Improved long-term outcomes through anticipatory care and preventative medicine.
- Whilst digital twins cannot replace real-world testing, they can simulate diverse patient populations, including underrepresented groups.

The Future[1,4]

Increased real-time integration with wearable sensors.

Expanded collaboration between hospitals and research institutions will support the development of open, validated models.

Augmented reality and virtual reality technologies could be used to interact with digital twins in a more immersive and intuitive way.

Advances in machine learning and AI will drive more precise simulations, stronger predictive modelling, and more efficient data processing, enhancing clinical decision-making.

Abbreviations

DBT: digital breast tomosynthesis; HER: Electronic Health Record; GDPR: General Data Protection Regulation; HIPAA: Health Insurance Portability and Accountability Act; VICTRE: Virtual Imaging Clinical Trial for Regulatory Evaluation.

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