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Innovative³ Digital Twin Technology in Healthcare: Real-Time Patient Models for Clinical Decision Support in Cardiology and Intensive Care

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Abstract - Digital Twin technology is gaining attention in modern healthcare as an innovative way to create virtual representations of individual patients by using real-time clinical and physiological information. These digital models allow healthcare professionals to better interpret patient conditions, particularly in high-risk areas such as cardiology and intensive care, where quick and accurate decisions are crucial. By combining data from medical records, sensors, and advanced analytical tools, Digital Twins make it possible to continuously monitor patients and design treatments that are more tailored to individual needs.This paper looks at how Digital Twin systems can be used in real clinical environments, with particular attention to conditions such as cardiogenic shock, where quick and accurate decisions are essential. Even though there is growing interest and research in this area, using these systems in everyday medical practice is still not very common. This is mainly because of challenges like handling large and varied data sources, the complexity of building and maintaining such systems, and concerns about protecting patient data.To address this, the study proposes a simple hybrid Digital Twin framework to support real-time decision-making in critical care. It focuses on helping doctors anticipate outcomes, explore treatment options, and respond more effectively to patient needs.

Keywords: Digital Twin, Healthcare AI, Cardiology, Intensive Care Unit, Clinical Decision Support, Personalized Medicine

1. INTRODUCTION

Digital Twin technology is slowly changing the way patient care is handled in modern healthcare. Rather than depending only on fixed medical records, it makes it possible to create dynamic digital models that closely reflect a patient's condition in near real time. These models bring together clinical findings, physiological data, and computational analysis to provide a clearer and more complete picture of a patient's health. This is particularly important in critical care settings, where even slight delays in decision-making can have a major impact on patient outcomes.

Traditionally, clinical decisions have often relied heavily on general guidelines, which can sometimes overlook the specific needs of individual patients. In simple terms, a Digital Twin can be seen as a continuously updated digital version of a patient, created using different types of medical data and designed to capture ongoing changes in their condition.

Recent developments in machine learning, as well as engineering and modeling of physiology, enable the creation of healthcare digital twins. Hybrid digital twin models, which integrate mechanistic modeling and AI of the cardiovascular system, have produced promising results in predicting patient outcomes and optimizing treatment plans. Most models still remain in early development, and none have been incorporated into clinical workflows. This paper reviews the state of digital twin technologies in healthcare, focusing on intensive care and cardiology. Using the available body of work as a guide, the paper identifies the most common obstacles, as well as the most important, unaddressed areas of research. This idea helps shape the development of a patient-centered Digital Twin that can support better decision-making for cardiogenic shock in the ICU.

2. CORE CONCEPTS OF DIGITAL TWIN TECHNOLOGY IN HEALTHCARE

2.1 Progression of Digital Twins from Engineering to Healthcare

Digital Twin technology originally developed in fields like engineering and manufacturing, where it was used to create

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virtual models of systems to monitor performance and anticipate potential failures. In these areas, digital twins function as continuously updated representations, allowing engineers to track changes in real time and improve how systems operate. Over time, this concept has been adapted for use in healthcare, where it is now applied to represent the unique physiological characteristics of individual patients.

In a healthcare setting, a Digital Twin uses different types of data to build and maintain a live model of a patient's condition. The use of artificial intelligence alongside biomedical and clinical data has played a major role in advancing these systems. As a result, Digital Twins can help track how diseases develop over time and allow healthcare professionals to explore possible treatment options, supporting more personalized and effective care in complex medical environments.

2.2 Core Components of a Healthcare Digital Twin

An integrated structure for developing and maintaining a virtual patient model is called a digital twin system and consists of several component parts. The first component is the real patient who is monitored multiple times and from whom a stream of physiological metrics is recorded.Data from wearables, diagnostic imaging, and electronic health records is combined to give a more detailed and overall understanding of the patient's health. These are some of the various possible retrievals of data which depict a patient's current health status. The next component is the data acquisition and processing component, which integrates and standardizes data from several clinical systems.

Once collected, the data is cleaned, organized, and prepared for further analysis to ensure consistency and usability. Finally, the computational modeling component, which integrates a combination of modeling and machine learning, allows simulation and prediction of biological systems and health outcome metrics.

In this context, hybrid modeling approaches that combine data-driven methods with physiological insights tend to deliver more reliable results. In cardiovascular digital twin research, models and simulation interactive data-driven approaches have yielded better outcomes. The last component is the clinical decision support component, which is primarily interactive-based and assists health care practitioners by providing the digital twin outcomes. Using predictive analytics and visualization dashboards, clinicians can track conditions of their patients and consider alternative courses of treatment (Ringeval et al., 2025).

2.3 Applications of Digital Twins in Cardiovascular and Critical Care

Cardiology and critical care are among the areas that can benefit greatly from the use of Digital Twin technology. It allows researchers to model important heart functions such as blood flow, cardiac movement, and electrical activity in a way that reflects each patient's unique condition. This makes it possible to develop personalized cardiovascular models that can help predict how a patient might respond to different treatment options.

These digital systems support clinicians in selecting and adjusting treatments based on individual needs, while also helping to track how a condition may develop over time. In critical care settings, Digital Twins can further enhance patient monitoring by working with real-time data. They continuously analyze a patient's physiological state, including vital signs like heart rate, blood pressure, and oxygen levels, and help maintain a clearer understanding of the body's internal balance. This ongoing assessment can support more timely and informed clinical decisions. These systems can also detect early warning signs of physiological instability, allowing for quicker clinical response. However, despite their potential, most digital twin applications are still at an early stage, with challenges in data integration, validation, and real-world implementation limiting their widespread use.

3. DIFFICULTIES IN APPLYING DIGITAL TWINS IN HEALTHCARE

Even though Digital Twin technology shows a lot of promise in healthcare, there are still several challenges that make its large-scale use difficult. One of the main issues is related to data—both its quality and how it is managed. Healthcare data comes from many different sources, including electronic health records, imaging systems, and monitoring devices such as wearables or ICU equipment. Bringing all this information together into a single, well-functioning system is not simple and requires clear standards and strong system compatibility.

Another major concern is the complexity involved in running Digital Twin systems. These models rely on a constant flow of data and advanced simulations to accurately reflect what is happening inside the human body. For this to work in real time, a high level of computing power and efficient processing methods are needed. Without proper optimization, it becomes difficult to keep the digital model updated in sync with the patient's actual condition.

In addition to technical challenges, issues related to data security and privacy also play a significant role. Since Digital

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Twins use highly sensitive patient information, it is essential to ensure that this data is well protected. Any weakness in security could lead to serious risks, so strong safeguards and strict adherence to healthcare regulations are necessary to maintain trust and ensure ethical use of patient data.

3.1 Issues associated with data integration and interoperability

Existing research highlights how essential real-time patient data is for Digital Twin systems to work effectively. In critical care settings, there is a constant flow of physiological information—such as heart rate, blood pressure, breathing patterns, and oxygen levels—that needs to be captured and made readily available to healthcare professionals. Having access to this data in real time allows doctors to respond quickly and manage patients more effectively.

One of the key strengths of Digital Twins is their ability to adjust continuously as a patient's condition changes. Unlike traditional monitoring systems that mainly send alerts, these models keep updating themselves using incoming data and improve their predictions over time. This makes it possible to take a more proactive approach, where potential complications can be identified earlier and addressed before they become serious.

However, putting this into practice is not straightforward. Medical data is often spread across different systems that do not easily connect with each other, making integration difficult. Because of this, the success of Digital Twin technology largely depends on creating standardized data formats and developing better methods to bring all this information together efficiently.

3.2 Predictive Capabilities in Cardiovascular and Critical Care

Digital twins are increasingly being explored for their predictive capabilities, particularly in areas such as cardiovascular care and critical patient monitoring. Their ability to process continuous data streams makes them especially valuable in situations that require rapid clinical decisions.

In cardiovascular medicine, digital twins can simulate blood flow dynamics, heart function, and disease progression. These models allow clinicians to evaluate the potential impact of different treatments before applying them in real-world scenarios, making them particularly useful in managing complex conditions such as heart failure and vascular disorders.Similarly, in critical care settings, digital twins support continuous monitoring and early detection of patient deterioration. By identifying subtle changes in vital signs, these systems can predict complications before they become clinically apparent, enabling timely intervention. This predictive capability is considered one of the most promising aspects of digital twin technology in healthcare.

Such digital twin models are designed to recognize critical and differential changes in one's vital signs to predict clinical deterioration that may remain unobserved. This predictive capability is frequently highlighted as one of the most promising opportunities of incorporating digital twin models into healthcare systems.

3.3 Technological and Ethical Considerations

Despite the potential advantages of digital twin technology, several technological and ethical challenges must be addressed before its widespread clinical adoption. One major difficulty lies in accurately modeling human biological systems, which are inherently complex and constantly changing due to multiple interacting factors. Ethical concerns also play a significant role, particularly regarding the use of sensitive patient data. Continuous data collection raises important questions about privacy, data ownership, and security. Without strong governance frameworks and privacy-preserving mechanisms, the use of such systems may lead to reduced trust among patients and healthcare providers (Ringeval et al., 2025). In addition to technical and ethical considerations, the successful implementation of digital twin systems depends on their acceptance by healthcare professionals. Clinicians must be able to understand, trust, and effectively use these technologies in their daily practice. Building this trust is essential for integrating digital tools with clinical expertise and ultimately improving patient outcomes.

4. FINDINGS

The findings of this study demonstrate that digital twin technology has strong potential to enhance clinical decision-making, particularly in cardiology and intensive care environments. By combining real-time patient data with advanced modeling techniques, digital twins enable continuous monitoring and more accurate prediction of disease progression. The analysis also shows that hybrid approaches, which integrate data-driven machine learning models with physiological simulations, provide more reliable and clinically relevant outcomes compared to standalone methods. These models are especially useful in complex cases where patient conditions can change rapidly.

However, the study identifies several critical challenges that currently limit the practical adoption of digital twin systems.

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Issues related to data integration, lack of standardized formats, and the need for high computational resources remain significant barriers. In addition, concerns regarding data privacy, security, and ethical use of patient information continue to impact trust and implementation.

Overall, while digital twin technology offers promising advancements in personalized medicine and predictive healthcare, further development and real-world validation are necessary before it can be widely adopted in routine clinical practice.

4.1 Integration of Real-Time Clinical Data

A notable aspect of the literature emphasizes the importance of real-time patient data in the construction of digital twin systems. Digital twins, in contrast to traditional healthcare models which rely on historical data, are able to adjust in real-time with the patient. Incorporation of real-time data from monitoring devices, wearables, lab data, and EHRs, can support the patient's digital twin. Research has shown that real-time digital twinning of a patient can enhance clinical monitoring.

Digital twin technology-enabled healthcare systems are built on the integration of patient monitoring systems, data processing pipelines, and predictive modeling systems. The overall operation of such a system is depicted in Figure 1.

According to Fuller et al. (2020), digital twins are described as systems that integrate real-time data with their corresponding computational models to provide the most up-to-date virtual models of intricate processes. In practical terms, this functionality allows clinicians to capture minute changes in the physiology of patients, which are often lost in distributed hospital information systems. In the same vein, Katsoulakis et al. (2024) emphasize that the successful implementation of a digital twin is predicated on effective data pipeline engineering that can process large volumes of heterogeneous clinical data. However, contrary to the earlier mentioned benefits, the available research also highlights that the integration of other clinical data is a significant technical obstacle. Clinical data is often generated by various devices and software systems that have different standards for data formats and communication protocols. Hence, the need to attain system integration and this data is of utmost importance for the effective operation of digital twin systems.

4.2 Predictive Modeling in Cardiovascular and Critical Care

The increasing use of digital twin models in predictive healthcare is an important step forward for medical technology. In cardiology and intensive care medicine, researchers are exploring how digital twins might predict the evolution of diseases and evaluate the effectiveness of different treatment approaches. Research in cardiovascular modeling shows that patient-specific digital twins can model several facets of the heart, including the functioning of blood flow, the dynamics of the vessels, and the overall performance of the heart.

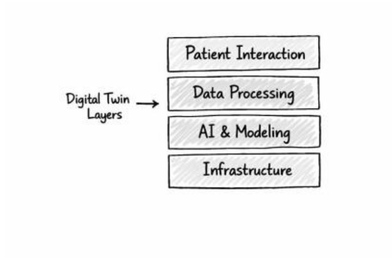
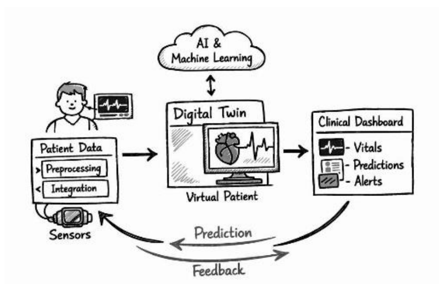


Figure 2: Architecture of a Healthcare Digital Twin System

The system has many layers including patient interfaces, processing of scientific data, AI modeling, and computation. These layers integrate and analyze data continuously in digital twin healthcare systems. Chakshu et al. (2021) for example, show that with the use of patient data and some form of inverse modeling, people can achieve cardiovascular behavior. Such models assist clinicians in evaluating the possible impacts of changes to their treatment actions on a patient's cardiovascular status, without having to rely on trial and error in real clinical settings. Beyond traditional models,



several studies show the growing importance of machine learning in digital twin systems. Some predictive systems are increasingly using hybrid modelling: a combination of traditional computed (biomedical) and other applied (scientific) concepts. Sel et al. (2024) believe that predictive models in clinical settings can maintain some part of their physiological models. In critical care environments, digital twins may also assist with predicting nursing actions before they are required. Excessively detailed continuous monitoring/reporting systems can recognize and report abnormal changes in a patient's condition before they reach a critical point. Such systems assist physicians in making educated clinical decisions and improve patient care in critical situations.

4.3 Technological and Ethical Considerations

The literature shows many interesting uses of digital twin technology, yet there are many technological and ethical challenges still to be addressed. Creating digital replicas of biological phenomena remains a daunting task. Defining individual biological behaviors of varying patients' bioentities is a challenge due to the multifactorial nature and individual variability of human physiology. Another important challenge is the lack of explainable AI (XAI) in digital twin systems. Many systems based on digital twins incorporate advanced machine learning (ML) systems. These systems are known to be 'black boxes' and in this event, healthcare professionals will be unable to control the ML system and will not be able to understand the outcome provided by the ML. As Rudnicka et al. (2024) noted, the use of XAI in the digital twins of healthcare is of utmost importance to provide the rationale behind the predictions to the healthcare professionals. Furthermore, the XAI is even more important when concerning the ethical issues of the constant request of digital twin systems to sensitive patient data; this requires substantial efforts in data governance and cybersecurity. According to Bruynseels et al. (2024), the first challenges that need to be addressed around the responsible use of digital twins in healthcare are the framework of patient consent, data protection, and accountability concerning the clinical decision support systems.

Overall, the studies suggest that although digital twin technology could considerably improve the personalization and prediction of health care, more research and technological improvements are needed to address the barriers to its secure use in clinical settings.

5. DISCUSSION

The findings of this study highlight the growing relevance of digital twin technology in transforming modern healthcare practices. By integrating real-time patient data with advanced computational models, digital twins offer a more dynamic and personalized approach to clinical decision-making. In high-risk environments such as cardiology and intensive care, the ability to continuously monitor patient conditions and simulate potential outcomes can significantly enhance the quality of care. However, while the theoretical benefits are substantial, practical implementation remains a challenge due to limitations in data integration, computational demands, and system reliability.

This is specifically important for real-time clinical data systems in cardiovascular medicine and ICU settings, where immediate clinical data interpretation is crucial for real-time data-driven decisions. A prominent theme in the literature is the shift towards predictive and personalized medicine. Classic clinical monitoring systems rely heavily on the interval data clinical methods of patient data, which can impede the recognition of deterioration. Unlike interval data clinical methods, digital twin-based SMS offer continuous real-time clinical data and predictive analytics, enabling clinicians to anticipate deterioration and intervene. Such a clinical approach can positively impact patient outcomes and subsequently, the healthcare system. Also, the literature indicates that digital twin technology is in its infancy. While advancements in AI and computational modeling have created more sophisticated digital twin systems, fully capturing the complexity of human physiology is still a significant barrier.

Models that try to encompass biological systems are faced with numerous interacting variables that can change at an individual level. Creating universally applicable models is considerably challenged by individual variability. One highly recommended consideration is the possibility of broad healthcare digital twin models through the lens of interdisciplinary collaboration. A healthcare digital twin is more likely to operate successfully when experts from computer science, biomedicine, engineering, data science, and any of the clinical practices collaborate. Even within the theoretical realm of digital twin systems, interdisciplinary collaboration is central to developing models into their first operational prototype. From the numerous ethics and regulations areas of digital twin technologies, patient data protection and privacy, transparent prediction algorithms, and accountability within clinical settings are most fundamental to reframing provider/patient trust. With the rapid advancements of ethical research, the digital twin model in everyday healthcare systems requires the same to ease integration of model-based diagnosis and treatment and digital twin technologies. Overall, most healthcare challenges posed by Digital Twin technologies can be reframed, but the question is if the challenge to the research community is to be digital technologies and links.

6. CONCLUSION

Digital twins are starting to be implemented in healthcare to allow new methods for patient management, diagnosis, and treatment. By using real-time clinical datasets with advanced models, clinicians can create virtual models to provide assistance with predictive analysis. Healthcare research suggests that digital twins are clinically applicable in real-time data analysis and continuous data monitoring, particularly in critical and cardiovascular care. When combined with digital modeling, machine learning can enhance digital twins for more accurate and timely risk assessments, prognosis, treatment options, and predictive analysis. There are many barriers that remain before digital twins can be effectively used in clinical settings. Literature identifies data integration, usability, and patient confidentiality as main obstacles to be addressed before clinical application. However, the gaps highlighted can be optimally addressed through collaboration among clinical practitioners, engineering, and data science research, and the resolution remains technologically feasible and invasive. As the digital phenomenon in healthcare continues evolving, digital twins are expected to become central to the intelligent and patient-centric ecosystem of the future.

Potential for more effective, tailored, and proactive patient care strategies could stem from their ability to integrate real-time tracking and predictive analytics.

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