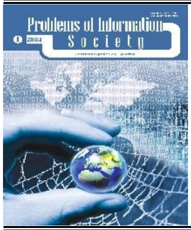
Problems of Information Society, 2024, vol.15, no.1, 98-105



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15 (1)
2024

Applications of digital twins in medicine and the ontological model of medical digital twins

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ARTICLE INFO

http://doi.org/10.25045/jpis.v15.i1.10

Article history:

Received 04 September 2023
Received in revised form
06 November 2023
Accepted 23 January 2024

Keywords:

Medicine
Physical object
Digital twin
Virtual object
IoT
Patient-oriented
Ontology
Model

ABSTRACT

The article demonstrates the applications, essence and possibilities of digital twin technology and explains the advantages of digital twin technology and potential challenges. A digital twin is a digital copy that can be used to simulate the status of a physical object or system. The integration of digital twin technologies with the Internet of things, Big Data and Artificial intelligence offers innovative solutions for quicker detection of arisen problems (or problems to arise) related to changes in a real physical object and for making relevant decisions. The development of such solutions in the healthcare is crucial for preserving human health and providing people with higher-quality medical care. It is possible to get an early diagnosis of the disease and the selection of a more effective treatment method on the produced digital twin by transferring the patient's physical characteristics and changes in his/her body to the digital environment.

The article analyzes medical digital twins, categorizing their benefits into patient health, cost reduction, self-management, and other benefits. In order to ensure adaptability and effectiveness in disease therapy and healthcare management decision-making, the patient-oriented ontology of healthcare is examined, and a four-level ontological model is suggested to create its digital twin. The creation of a patient-oriented digital twin of healthcare requires the creation of a digital twin of existing physical objects at each level of its ontological model. The creation of digital twin in healthcare opens wide opportunities for making decisions on provision of safe and high-quality medical care to patients.

1. Introduction

Today, the world is experiencing fourth industrial revolution or Industry 4.0, in which Internet of Things (IoT), "smart factories" and "smart devices" are replacing humans in production. The opportunities of the technologies provided by Industry 4.0, the widespread use of the intelligent and self-regulating "Internet of Things" paradigm connected to the dynamic network infrastructure have created conditions for the digitization of healthcare, the emergence of new medical mobile applications and the rapid integration of high-quality mobile devices into clinical practice. The most successful consequence of this trend includes the development of modern information technology complexes that enable real time information progressing, and research in this area is constantly progressing (Mammadova et al., 2023).

The phenomenon of "digital transformation" has emerged as a result of the rapid use of the advanced information technologies application, and the expansion of its boundaries and possibilities. Digital transformation enables the transformation of data into information and knowledge, the use of newly obtained knowledge for effective decision-making (Reis et al., 2018). Digital twins (DT), one of the base technologies of digital transformation, act as a digital copy of the physical object or process they represent, enabling real-time monitoring and evaluation of the process independent of location.

To this end, this article analyzes the studies on the creation of digital twin, demonstrates the possibilities of creating medical digital twins for improving the quality of medical services, and develops and proposes a patient-oriented ontological model of medical digital twin.s

2. Formation of digital twin ecosystem

The history of the idea of digital twin begins in the 1950s. At that time, NASA (National Aeronautics and Space Administration - US National Space Agency), GE (General Electric) and other industrial manufacturers were developing abstract digital models of equipment to account for equipment functions and life cycle through simulation modeling (Lim et al., 2020).

The University of Michigan (present Florida Institute of Technology) implemented the concept of digital twin for the first time in production in 2002. Defined as a "virtual, digital equivalent of a physical object", a digital twin was proposed as a conceptual model based on Product Lifecycle Management (PLM) (Grieves et al., 2017). At that time, it was technologically difficult and expensive to make this technology suitable for general use. However, ten years later, the rapid development of Big Data, IoT, Artificial intelligence (AI), 5G and Internet of Medical Things (IoMT) made it possible to implement this idea (Mammadova et al., 2023). M. Grieves introduced the term digital twin in 2011, and a three-dimensional model of digital twin was proposed based on the idea of "virtual digital equivalent of a physical product" in a technical document published in 2014 (Vassolo et al., 2021).

Although there is no universally accepted definition of digital twin, there are many definitions of digital twin technology depending on the intended use and possible application area. For instance:

• DT is a digital copy of animate or inanimate physical object (Grieves, 2014);

• DT combines sensor data, computer modeling and AI algorithms and can be described as a digital mirror of the created real world (Jones et al., 2020);

• DT allows to test and forecast the effects of the implementation of certain options, solutions, to visualize the obtained results in a convenient form etc (VanDerHorn et al., 2021).

A connection between the DT and its real-life counterpart that ensures a continuous and reliable data flow is a prerequisite. Realizing this connection through the use of developing sensor technologies and IoT applications has made it possible to realize a variety of interesting processes, like the real-time monitoring of physical devices in an industrial setting.

IoT devices, various sensors and analytical applications interacting with them are applied in solving a number of administrative management, logistics and treatment-diagnostic issues. The worldwide global connectivity of IoT can be used for collecting, processing, and effective use of various types of medical data, such as security, diagnostics, therapy, treatment, medicine, management, finance, daily activity, etc. (Silva et al., 2021).

IoT devices enable the real-time data collection required to create the DT of a physical component and relate the physical environment with its virtual image. It should be stated that because the data gathered by the aforementioned IoT is vast in scope, big data analytics is essential to the creation of an effective DT. Cloud computing is the best platform for big data processing and analysis. The increasing availability of medical data allows for a more thorough analysis of the interactions underlying large volumes of information consisting of various datasets with the help of Big Data technologies. The analysis of Big Data makes it possible to discover unexpected interactions and patterns beyond human capabilities. Big Data technologies, for instance, allow simultaneous processing of databases of patients' medical histories, genome data and medical research reports, and ultimately obtaining the necessary information to make a better decision for the treatment of a specific patient (Mammadova et al., 2022). Based on the collected data, the AI is referred to create the DT. Machine learning (ML) methods, one of the leading areas of artificial intelligence, are used for training, validating and optimizing the digital model. ML ensures the creation of the most suitable models by applying methods on datasets formed on the basis of past experience.

The general interaction between IoT, Big Data, AI/ML and DT is displayed in Fig. 1.

As its physical counterpart changes, DT is also updated and modified. In order to determine the physical object's current state, location, function, composition, etc. it uses sensors. The unstandardized data is delivered in real time to the virtual twin, resulting in a dynamic depiction of the situation. DT can learn from this data through machine learning, field experts, and identical twins (Panahiazar et al., 2014).

DT includes the following characteristics (Grieves et al., 2017):

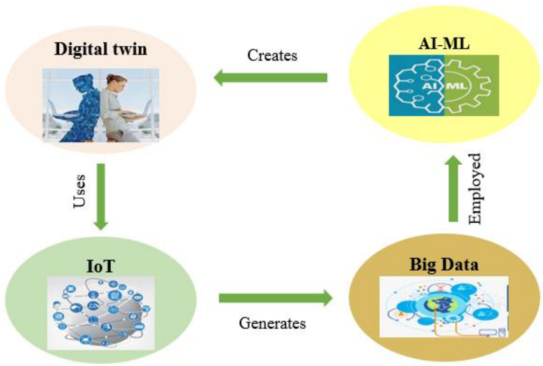

Fig. 1. Relationship between IoT, AI/ML, Big Data and DT

1. Connectivity - connection between the DT and its counterpart in real life is necessary to ensure an uninterrupted and reliable data flow;

2. Homogeneity - homogenization of data from different sources should be implemented;

3. Reprogrammable - as the volume of regularly collected data increases, DT also develops and provides smarter decision-making through artificial intelligence;

4. Modularity- DT can allow the manufacturer to learn which particular components of the device are underperforming.

The integration of the following 3 main types of DT ensures the formation of the DT ecosystem (Xin Liu et al., 2023):

- A digital twin prototype (DTP) is a virtual analogue of a real object that contains all the data for the production of the original one;
- A digital twin instance (DTI) contains data about all the characteristics and operation of a physical object, including a three-dimensional model, and operates in parallel with the original;
- A twin aggregate (DTA) is a computing system of digital twins and real objects that can be controlled from a single center and share data internally.

The applications of DT technologies in various fields are increasing day by day, this trend becoming more noticeable due to advancements in technologies such as IoT and cloud. The DT market is estimated to grow to 35.8 billion USD by 2025, whereas these indicators amounted for 3.8 billion USD in 2019 (Liyanage et al., 2022).

3. Medical digital twins

Modern medicine, which is forming in the environment of Healthcare 4.0, includes not only the treatment of patients, but also the management of healthcare, the prevention of diseases and the processes of health restoration. With the increasing popularity of information communication technologies, people's demand for health services is shifting from offline mode (offline service) to new online models. Currently, the field of online medicine has not developed enough to serve the elderly, chronically ill and people with infectious diseases. Positive outcomes can be obtained by using the advantages of digital twins in resolving such problems.

Providing citizens with high-quality and safe medical services, providing information support for medical research and continuous medical education, making both doctor's decisions and management decisions necessitated the provision of the tools ensuring complex digitization of healthcare. In order to achieve these aims, a wide range of modern technologies have emerged (Barricelli et al., 2019).

Healthcare is considered to be one of the promising areas where DT from these technologies can have a revolutionary effect. DT is designed to provide more effective medical interventions and help doctors and medical technologies understand the patient's health status (Mammadova et al., 2022). One of the main conditions for the application of DT in medicine is its physical object in the real world. A medical DT is a dynamic digital model containing all the input data about a physical object or medical system. Medical digital twins can be used to tackle many problems in healthcare. These problems include early diagnosis of any disease in the initial stage and monitoring of subsequent development trajectories, optimization of the time of medical assistance, development of personalized medicine, clarification medication action mechanisms, etc. These benefits are presented in Table 2, categorized by patient health, cost reduction, self-management, and other aspects.

Table 1: Advantages of digital twin technologies

Patient health	Cost reduction	Self-management	Other advantages
• Better diagnostic; • Minimally invasive intervention • Reduction of errors in reverse effects.	• Acceleration of new medication discovery; • Reduction in the treatment duration; • Rapid clinical trials; • Provision of technical	• Patients managing the parameters of their treatment; • Patients are aware of their body data.	• Equal treatment of patients • Reduction of testing on animals.

	services.		

4. Related work

Currently, various applications in the testing phase related to the application of digital twins in medicine are being developed (Coorey et al., 2020; Oikonomou et al., 2017; Golse et al., 2021; Karakra et al., 2018). The benefits of DT can be applied to the health sector primarily in the areas of disease therapy and health management.

Therapy of diseases:

Today, the main medical applications of DT are in the field of disease therapy. For example, Siemens' Healthineer DT system based on the human heart presents patients with 3D images of their organs and provides simulation of their physiological state, personalized heart therapy based on artificial intelligence (Coorey et al., 2020). It is also possible to predict the postoperative condition of the patient with the help of DT. For example, liver failure is a leading cause of postoperative mortality in liver patients, and treatment options are adjusted through DT simulation surgery to predict the development of such risks (Oikonomou et al., 2017). Through this technology, it is possible to predict the patient's response to treatment in order to predict potential complications.

As another example, the mission of the DT system created by Heikki Laaki and his team is to enable DT remote surgical communication for reliable communication by providing communication tools in critical applications (e.g., remote surgery supported by cellular networks). This study proposes methodological basic principles for the further wide application of DT technology in surgical medicine (Golse et al., 2021).

DT can provide different treatment options for different patients with the same disease and accelerate the development of personalized medicine. The essence of personalized medicine covers the individualization of medicine therapy based on the personal data and genotype of a specific patient (Karakra et al., 2018). Predicting the tendency towards personalized medicine and early disease identification at the stage of subsequent preventative measures is envisioned as a new paradigm in healthcare. (Mammadova et al., 2019).

In order to prescribe personalized medicine, DT first collect all information about the patient in his/her electronic health record (EHR) and generate his/her digital twin. EHR is an electronic application where health information is stored in a private, secure and confidential environment. EHR records the data of an individual throughout his/her life from the day of his/her birth. Individual data for each patient (diagnostic descriptions, prescriptions, laboratory tests, observation results) are stored in EHR (Hood, 2013),. Based on these data, generic medicine for a certain disease are checked and selected from the drug database on the DT formed on the basis of this information. The doctor involved in the process updates the patient's DT based on the results of the analysis obtained as a result of the inspection. This process is continuously repeated until the best medicine is found and stored in the database. Finally, the doctor treats the patient according to personalized medicine. Thus, it is possible to prescribe entirely new medications at individual doses and forecast patients' reactions to certain medications based on the processing and analysis of a vast quantity of genetic information linked to them through DT (Golse et al., 2021).

Health care management:

In recent years, there has been an increasing trend in the number of healthcare facilities and healthcare personnel, healthcare facility assets and insured persons, as well as per capita costs for hospitalization (Xin Liu et al., 2023). Although the necessary resources are available for most medical procedures, as the population grows, there is a severe lack of hospitals and medical specialists in this field. DTs, distinguished by their efficacy in this field, provide well-organized tools for monitoring people's physical condition in real time and create a reliable basis for people to use cloud-based health services.

DT Healthcare (DTH) and Health 4.0 offer an innovative approach to the advancement of medicine in the future. DTH is a novel type of medical concept applied in medical activities or medical systems. It provides fast, accurate and efficient healthcare services through the use of DT technology (Qiao et al., 2020). For instance, physical indicators of people can be obtained through sensors such as smart watches and digital models based on this data can be created to manage the individuals' mental health. Through these technologies, it was revealed that the changes in individual's emotional state affect the state of their bodies. Based on the data collected on the indicators characterizing the physical state, it is possible to identify the cause of stress and to take action to improve patient's health by minimizing the causes of stress. In addition to providing high-quality services to users in the integration of cloud computing and DTH, the system is expected to provide user data storage in the cloud using privacy mechanisms to safeguard medical data.

These opportunities created by DT are very crucial in providing medical care to patients, which is the primary component of healthcare. By transferring the physical characteristics and medical data of the patient to the digital environment, DT offers innovative solutions in determining the accurate diagnosis and treatment process as well as forming personalized medicine. An ontological analysis of patient-oriented medicine and the establishment of an ontological model of the appropriate medical DT are essential for providing patients with high-quality medical care.

5. Ontological model of patient-oriented medical DT

In the healthcare sector, being heterogeneous, medical data is collected from various sources, and there is a need to understand the common semantics of this data. A possible solution to this semantic interaction problem is possible by using an ontological approach.

Ontology is a set of general and specific terms with a hierarchical structure used to describe and present the subject area (Sacchi et al., 2015). The task of ontologies is to maximally represent the semantics, properties and inter-word relations of terms. In recent years, standardized ontologies have been developed in many fields. However, each ontology depends on the subject area, its specific components and the semantic relations between them. Taking these factors into account, an ontological model of patient-oriented medical DT in the healthcare system is proposed. Fig. 2 describes the four-level hierarchical architecture of the ontological model.

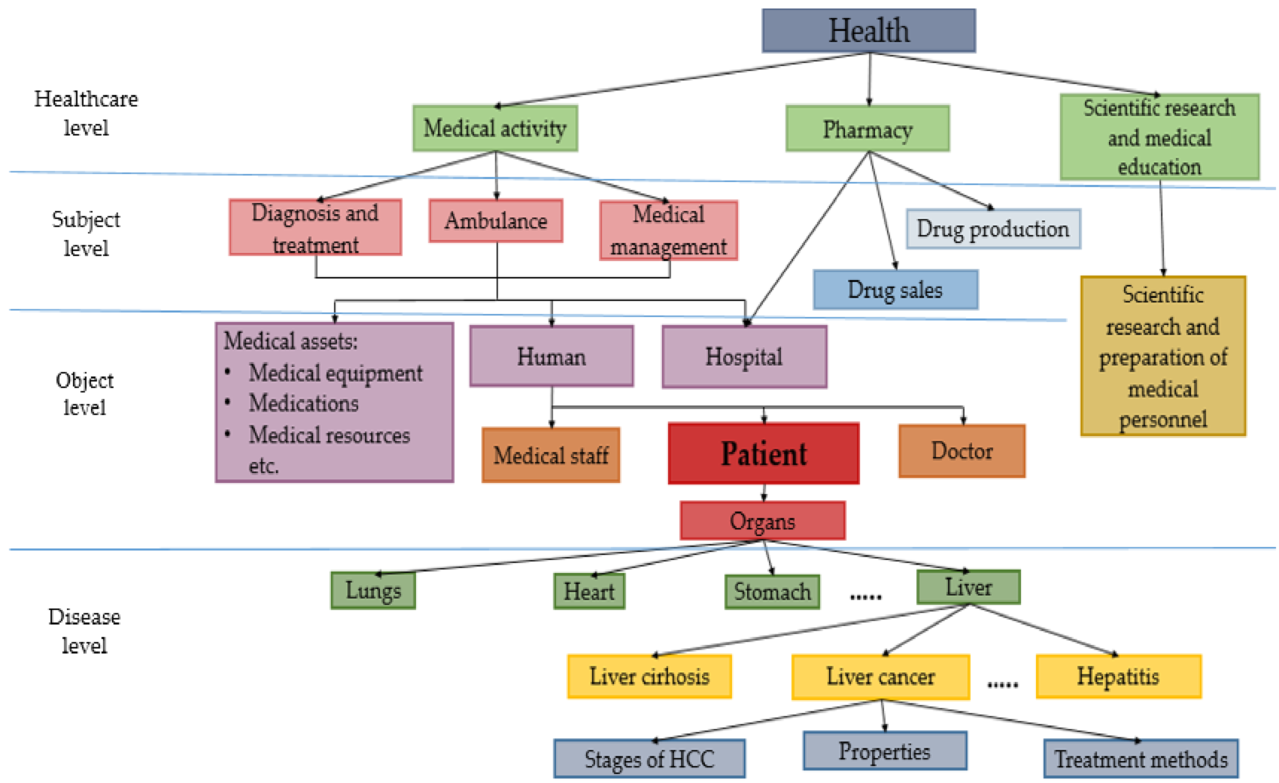

Fig. 2. Ontological model of patient-oriented medical DT

As Fig. 2 shows, the development of a complete DT of health care is a long-term and step-by-step process. The development of such a DT requires an ontological analysis of health care in terms of personnel, material, and financial provision along with patient-oriented medicine and the creation of an appropriate DT. It is possible to create a patient-oriented medical DT in a healthcare system with levels by referring to the ontological model described above. Level I is called the healthcare level of the ontological model. It includes medical activity, pharmacy, medical education. Level II is the subject level, which includes departments such as ambulatory care, emergency care, dentistry, medicine production and medicine sales. Based on Levels III and IV of patient-oriented medical DT, current researches and applications are conducted in the sphere of developing a DT on individual human organs and diseases related to these organs.

As an example of the objects that comprise Level III of the ontological mode, Fig. 3 illustrates the process of creating its virtual object (DT) based on the data gathered from the physical object.

A virtual object is software consisting of a set of applications that explain the behavior of a medical object on a computer. Applications are used as a real-time monitoring system for the object's activity, and this system operates throughout the entire life cycle of the object. Developing a visualization system for monitoring the activity of a virtual object is one of the essential processes. A visualization system – represents data management models in various fields of medicine, information received from various sources and outcomes visually. This enables effective monitoring, control and management of processes occurring in a medical physical object.

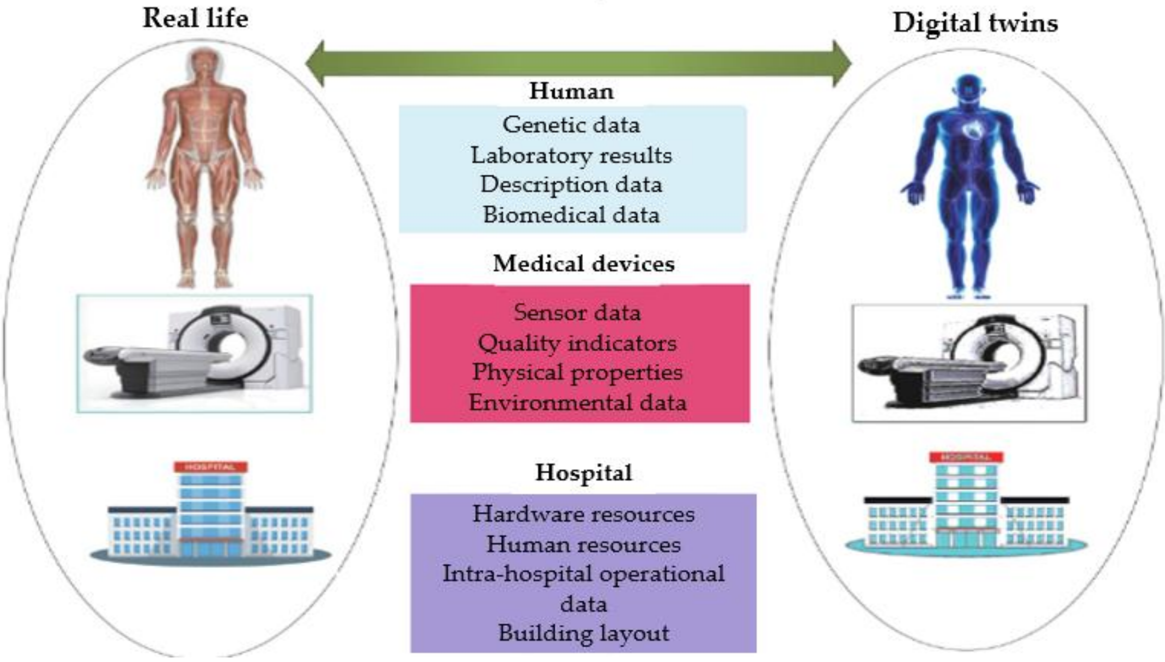

Fig. 3. Main component of air-water heat exchanger

Similarly, Level IV of the ontological model - that is, certain parts and organs of the human body can be digitally replicated. Currently, a digital twin of the human heart is now being tested to address various medical issues (Coorey et al., 2022). It has been created using data collected by medical devices to simulate the physiological processes of a real person. It should be noted that each person's heart is different, so universal anatomical models based on population data are not beneficial in this situation. A digital heart twin, on the other hand, reflects the individual characteristics of each patient.

Currently, the possibilities of digital twins of the human heart to increase their effectiveness in the diagnosis, prognosis and treatment of various heart diseases are being investigated and their practical applications are being analyzed. The successful outcomes and the processes and technologies applied for the creation of the cardiac DT can serve as a model for the development of other medical DT.

In order to implement traditional systems or devices, they must be first designed and then tested. However, simulation of virtual DTs allows for virtual testing before physical devices are made. Errors are inevitable in traditional production and it is challenging to simulate the real environment during the system or process realization stage. DT uses real-time monitoring data to update the model dynamically over the course of a physical system's lifecycle. This allows the model to track the changes in the complex environment along with representing the device status.

DT has numerous drawbacks in addition to its effectiveness in the field of medicine; these are outlined in Table 2:

Table 2: Drawbacks of digital twin technologies

Data	Inequality	Other risks
• Sharing sensitive, personal information; • Presence of third parties using data; • Poor data quality.	• The inability of individuals with poor technological skills to use these technologies.	• Responsibility and accountability; • Decreased self-care; • Environmental risks; • Physical technological risks.

6. Conclusion

This article explored the possibilities of the DT technology, one of its fundamental technologies and occurred as a result of digital transformation, and reviewed relevant works. The application of DT technology provides a favorable ground for automating decision-making and its implementation, as well as, continuous monitoring and evaluation of the quality of medical care, using heterogeneous and unstructured data gathered from various sources. The DT technology, developed through the integration of new generation digital technologies, particularly contemporary IoT tools and AI systems, allows simulating the state of a real physical object on its virtual digital copy. This also ensures quicker and more accurate decision-making by eliminating the problems occurring in the physical object on its reproduction. Given these advantages, developing a patient-oriented DT is vital for protecting patient health, enabling the quick detection and elimination of any disease, which is one of the most crucial problems facing the healthcare system. Given the significance of solving this issue, the article proposed an ontological model of four-level patient-oriented DT in the healthcare system. In the perspective, the deepening of researches on the object and disease levels of patient-oriented medical DT enables to conduct an ontological analysis in terms of subject objects such as healthcare staffing, material supply, medicine therapy, etc.

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