230. 3D PRINTING IN MEDICINE: CURRENT STATE AND FUTURE POTENTIAL

Baikou A.S.

*Belarusian State University of Informatics and Radioelectronics
Minsk, Republic of Belarus*

Kaspiarovich N.G. – Senior Lecturer

This paper analyzes the current implementation of additive manufacturing technologies in modern medicine and explores emerging applications as the next stages in the evolution of regenerative medicine.

3D printing, or additive manufacturing, is a production technique that creates a final product by depositing individual layers on top of each other based on a digital 3D model. In contrast, subtractive manufacturing, such as CNC machines, carves the desired shape out of a solid block of material. 3D printing significantly minimizes material waste by utilizing only the precise amount of material required for the object. The process begins with the creation of the object in CAD software, which is then processed by 3D slicing software to convert the model into a series of thin horizontal layers. This layered model is then translated into G-code, providing the 3D printer with precise geometric instructions to execute the build. Modern additive manufacturing encompasses various technologies, including Fused Deposition Modeling (FDM), Stereolithography (SLA), Digital Light Processing (DLP), Material Jetting (PolyJet), Selective Laser Sintering (SLS), Binder Jetting, and Direct Metal Laser Sintering (DMLS). Each method employs a unique technique to deposit, join, or solidify materials under computer control to construct complex shapes layer by layer. The technical differentiation between these methods lies in the physical state of raw material and the energy source used for its transformation. FDM operates through the extrusion of thermoplastic filaments that rapidly solidify upon deposition, forming a rigid structure. In contrast, SLA and DLP utilize vat photopolymerization, where a focused UV light source selectively cures liquid photosensitive resin layer by layer, solidifying it. PolyJet functions by dispensing microscopic droplets of photopolymer through multiple print heads, which are immediately cured by UV lamps. Powder-bed fusion techniques, such as SLS and DMLS, employ high-power lasers to melt and fuse polymers or metal alloys into a solid mass. Binder Jetting works by depositing a bonding liquid onto a powder bed, joining the particles without the application of direct heat. These distinct mechanical and chemical processes determine the object’s shape, structural integrity, and properties, providing a versatile foundation for various manufacturing processes. Although originally developed for industrial prototyping, the high precision and capability for patient-specific customization have enabled the adoption of these technologies across various medical disciplines.

The integration of 3D printing into medicine is driven by several key advantages. The most important are cost and time savings. In-house additive manufacturing allows medical facilities to minimize reliance on third-party vendors, drastically reducing production time and cost. A part that would require months of lead time and substantial financial investment to build and ship by a third-party can be produced in a couple of weeks, with expenses restricted solely to raw materials. The other major advantage of 3D printing is customization. 3D printing allows for the creation of devices tailored exactly to the patient’s anatomy based on MRI or CT scan data, making it fully personalized, instead of “one-size-fits-all”. This localized production model also accelerates the process of structural adjustments. Consequently, the use of patient-specific surgical guides and anatomical models reduces operative times, mitigating surgical risks and lowering hospital expenses, ultimately improving overall patient satisfaction and resource allocation [1]. Additionally, this approach to manufacturing promotes environmental sustainability by significantly reducing the carbon footprint associated with traditional global shipping and supply chains.

Considering these advantages, 3D printing is being implemented across several distinct healthcare departments. In physical therapy, occupational therapy, and prosthetics, FDM is frequently used for fabricating upper extremity orthotics, check sockets, hand pieces, and custom covers for prosthetics due to its cost-effectiveness and durability. FDM is also employed in clinical education, allowing staff to train on anatomical models and helping patients visualize their conditions. In radiology and surgery, high-resolution photopolymer technologies such as SLA and PolyJet are used to produce accurate anatomical models based on patient scan data. These models assist with complex surgical planning and advanced staff training. Beyond direct patient care, FDM is utilized to rapidly manufacture replacement parts for medical device repairs and to design custom solutions for preventative maintenance. Currently, dentistry remains one of the most commercially significant medical fields. Using precise technologies such as SLA and DLP, dental professionals produce nightguards, temporary bridgework, dentures, implant radiographic appliances, and surgical implant placement guides.

The transformative impact of 3D printing on healthcare is clearly reflected in its rapid economic growth. According to Grand View Research, the global 3D printing market size was valued at $8.52 billion in 2023. Driven by its increasing evolution and effectiveness in resource usage, the market is projected to expand at a Compound Annual Growth Rate (CAGR) of 18.5% and is expected to exceed $27.29 billion by 2030

(Figure 1) [2]. This highlights the transition of 3D printing in the medical field from an experimental niche to a commonly used practice.

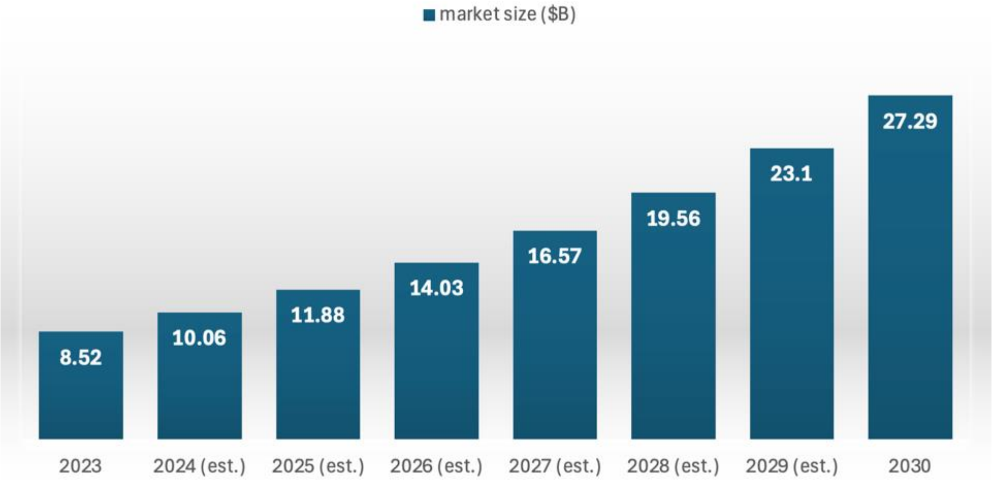

Figure 1 – Forecast of the Global Healthcare 3D Printing Market Size (USD Billion) for 2023–2030

As additive manufacturing technologies mature, more opportunities will emerge. The most ambitious frontier is 3D bioprinting – the process of combining cells, growth factors, bio-inks, and biomaterials to fabricate living tissues. Currently, scientists are successful in creating organ models and tissues that can be used to research drugs and potential treatments. However, the ultimate goal of bioprinting is the fabrication of complex, full-sized, vascularized organs such as kidneys and hearts [3]. Utilizing a patient's own stem cells, this approach could potentially eliminate transplant waitlists and mitigate donor rejection. Furthermore, 3D printing is poised to transform pharmaceutics through highly personalized medicine. Its precision allows for the adjustment of the active material down to the exact milligram tailored to an individual's weight and metabolism, which is particularly beneficial for the elderly and children, as they usually require non-standard dosages. Additionally, the technology enables the creation of "polypills", combining multiple medications with distinct release profiles into a single dosage form. Although not widespread yet, it is already being used on selected medications, and scientists around the world are actively researching this topic [4]. Another emerging future application of additive manufacturing in the medical field is the development of 4D printing, which introduces time as the fourth dimension. 4D-printed parts will change their shape or properties over time in response to external stimuli. This facilitates the development of smart implants that adapt to the patient's anatomy after implantation. For example, researchers are developing a material that can be inserted in a compact form and then expand or transform inside the body to fit its structure. This would make surgical procedures much less invasive and easier, and improve long-term implant performance. The concept of 4D printing is still largely in the experimental stage, but it is being actively studied as a next step beyond traditional 3D printing in regenerative medicine [5]. Despite these promising additions, the ultimate success of additive manufacturing in medical fields relies on more than just technological maturity. An overhaul of current regulatory measures will be required for its widespread clinical adoption. Because bio-printed organs and personalized polypills are entirely custom-made, standard quality control measures cannot apply to them. Establishing new safety guidelines and standardized testing for biomaterials remains a critical, unsolved challenge for global healthcare.

In conclusion, 3D printing serves as an enabler of personalized medicine, effectively addressing the limitations of standard medical devices. By optimizing costs and streamlining the production of patient-specific implants and tissues, this technology significantly enhances clinical outcomes and accessibility to advanced treatments. The continued evolution and integration of additive manufacturing suggest it will rapidly become a fundamental standard in healthcare delivery, profoundly improving patient survival rates and satisfaction.

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