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Development of the 3D printing market and its application in medicine

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Abstract

According to forecasts and predictions by leading analyst firms, several million 3D printers were expected to be sold annually by 2020, with consumer devices in virtually every home being the driving force.

This article aims to conduct a systematic literature review (SLR) of various applications of 3D printing in medicine. The author based his considerations on Polish and foreign literature, studying scientific articles and electronic sources. The analysis included a review of literature and online sources from 2012–2023. The author used the following professional, academic databases to gather scientific literature: Library of Science, Google Scholar, ScienceDirect, Emerald, Emis Intelligence, Passport, and Statista.

This article defines the concept of 3D printing, presents the development of the 3D printing market, and indicates market trends and applications of 3D printing in medicine.

The analysis made it possible to determine the extent of the phenomenon and to identify the main trends that are observed in the field and environment studied.

1. Introduction

3D printing opens up many potential medical applications, such as anatomical models for training purposes, patient organs printed from ultrasound scans, implants or surgical instruments. Polish specialists, surgeons, and cardiologists are already using 3D printing to prepare for surgery.

Hospitals and laboratories have invested in 3D printing technology hardware, software, and services. Nearly 3% of large hospitals as well as medical and research institutions already have on-site printing facilities. They print models of

the heart to help cardiac surgeons prepare for surgery, or joint components based on a natural prototype. In the next three years, one in four surgeons will prepare for surgery using 3D-printed, complete patient models (Piątek, 2018).

From the author's perspective, the analysis of the medical 3D printing market is important for many reasons. 3D printing technology has started a revolution in many fields, including medicine, which can bring many benefits and improve the quality of healthcare. Analyzing the medical 3D printing market is crucial to understanding the potential of this technology and finding new ways to improve patient care, diagnosis, treatment, and quality of life.

The primary purpose of this article is to present issues related to the development of the 3D printing market and its application in medicine.

The research problem is to determine how the development of the 3D printing market can be applied in medicine. To examine the research problem stated above, the following questions were formulated.

1. What are the latest trends and innovations in 3D printing related to medicine?
2. What are the main challenges and limitations of 3D printing in medicine?
3. What are the primary and potential benefits of 3D printing in medicine?
4. What are the prospects for the development of the 3D printing market in medicine in the coming years?
5. What are the potential limitations of 3D printing in medicine?

The research questions provided a starting point for research and analysis that will provide a deeper understanding of the research problem and contribute to the development of knowledge about the growth of the 3D printing market and its application in medicine.

The author based his considerations on Polish and foreign literature, studying scientific articles and electronic sources. The research was focused on 3D printing, while the subject of the study was the development of the 3D printing market and its application in medicine.

2. Theoretical framework of the research

3D printing is an additive (also known as incremental or cumulative) method, regardless of the 3D printing technology used objects produced by this method are created by building up the model layer by layer. This makes it possible to achieve effects that are difficult to reproduce using traditional manufacturing methods, such as casting. 3D printing does not require molds, making it possible to produce models of complex shapes relatively quickly and inexpensively. The variety of materials that can be used and the wide availability of the technology allow it to be used in a wide range of fields (Lesiński, 2020).

Thus, the 3D printing process enables the creation of three-dimensional objects based on a model generated in computer-aided design (CAD) software. 3D printing is part of the additive method, in which objects are created by adding elements; 3D printing creates an object layer by layer. Among other things, this is what distinguishes 3D printing from other object manufacturing technologies, such as machining, casting, or forging processes, in which material is removed from a stock component or poured into a mold and shaped using dies, presses, and hammers (Lesiński, 2020).

3D printing was known as rapid prototyping in the 1980s. Dr. Kodama filed for the first patent for the technology in Japan in May 1980, but his application was rejected. Six years later, in 1986, Charles Hull received a patent for his stereolithography (SLA) device and subsequently became one of the founders of 3D Systems, which sold its first SLA system in 1988. The next major milestone came in 1987 when Carl Deckard filed for a patent for the selective laser sintering (SLS) process. The patent was granted in 1989 and the process was licensed to DTM Inc., which was later acquired by 3D Systems. That same year, Scott Crump, co-founder of Stratasys Inc., filed a patent application for fused deposition modeling (FDM). The company received the patent in 1992 and still holds it today, while FDM is one of the most widely used 3D printing technologies (BIS Research, 2022).

In the following years (1990s and 2000s), the 3D printing market became increasingly competitive. Several companies, such as Objet Geometries, Sanders Prototype Inc., and several others, entered the market in the 1990s and 2000s; however, only three of the original companies – 3D Systems, EOS GmbH, and Stratasys Inc. are still operating as independent companies today, while others have been acquired or merged with other companies.

An important year in the development of 3D printing was 2000, when the 3D printing market showed tremendous growth, the first 3D-printed kidney was printed, but it took another 13 years to achieve a successful transplant.

The first high-resolution color 3D printer was introduced by Z Corporation in 2005, and 3D Systems produced the first 3D-printed prosthetic limb in 2008.

A critical stage in the development of 3D printing came in 2009 when the FDM patent went public, leading to a drop in the price of FDM 3D printers and increased innovation in FDM 3D printers. More and more 3D printing materials are being developed every year, and companies are looking to seize the opportunity to gain market share (BIS Research, 2022).

According to Gibson, Rosen, and Stucker (2015), "3D printing, also referred to as rapid prototyping or free-form manufacturing, is a manufacturing technique that creates physical objects by depositing materials layer by layer" (Gibson et al., 2015). Kianian (2019) states that 3D printing, also known as incremental manufacturing, is "the process of creating physical objects by adding successive layers of material based on a digital model or design."

Nkomo, Sibanda, Gwamuri, Igadwa (2019), "3D printing is a form of additive manufacturing in which objects are created by adding layers of material, often in the form of liquid, powder or filament, under computer control from a digital model or design." (Gwamuri et al., 2019).

In contrast, Mahamood, Khader, and Ali emphasize that: "Three-dimensional (3D) printing, also known as additive manufacturing, is the process of creating solid objects from a digital file. Creating a 3D printed object is done through an incremental process" (Mahamood et al., 2016).

3D printing uses an incremental manufacturing process in which products are built layer by layer through cross sections (Barry and Zarb, 2012). 3D printing enables low-cost, bottom-up production of objects with complex geometries that are difficult to manufacture using traditional methods (Jun et al., 2015). The advent of 3D printing shortens the design and development cycle of thermoformed products. 3D printing increases productivity and promotes product development (Feixiang et al., 2016).

Thus, 3D printing is the process of producing a three-dimensional component based on the same computer model. Each layer is a thin horizontal cross-section of the printed object. Traditional manufacturing technologies create the part by subtracting material and cutting with a milling machine, but more material is consumed. Each 3D process consists of three stages listed below (Skrzek, 2020):

– Modeling – three-dimensional models can be built using CAD software, downloaded from the Internet, a 3D scanner, or possibly by taking photos and then using computer software for photogrammetry. An incorrectly developed three-dimensional model can be repaired – the easiest will be with a self-created one using a program; correcting a model downloaded from the internet is slightly more complicated.

– Printing – before you start printing, you should check the correctness of the three-dimensional model – if it is made correctly, you need to select parameters, such as temperature and layer height. When setting the parameters, you need to consider the material, method, and geometry of the part. Another option is to use software that will divide the model into layers. Printing can take from a few minutes to a few days, depending on the method, the size of the part, the complexity of the model, and the machine itself. Once the process is complete, unnecessary material is removed, and the workpiece is detached or removed from the table.

– Finishing – the surfaces of the printed parts are porous, so they are still subjected to finishing treatment to smooth them out. The type of finishing depends on the material used. In the most popular method, FDM, acrylonitrile-butadiene-styrene (ABS) polymer can be treated using chemical vapor processes based on acetone or similar solvents. For metal parts, the surface can be improved by grinding, for example. In the finishing process, supports are removed, i.e., elements whose function is to support the main structure to protect it from deformation. There are methods for printing colored parts; finished parts can also be varnished or painted.

3. Research methodology

The author used the method of secondary data analysis (desk research) to gather information on 3D printing and its application in various sectors, especially in the medical field. Secondary data analysis refers to examining, interpreting, and extracting information from the data previously collected and shared by other institutions or organizations. Secondary data is already known and compiled for another study or analysis. Secondary data analysis uses existing data to extract new information, identify trends, relationships, and dependencies and answer research questions. In the literature review, the author used the following combinations of keywords and logical operators ("3D printing," "3D printing market," and "application of 3D printing in medicine"). For the desk research analysis, the following professional databases were used for data collection: Google Scholar, ScienceDirect, Emerald, Emis Intelligence, Passport, and Statista. The study gathered literature for this article and the research problem stated above. The analysis included a review of literature and online sources from 2012–2023.

4. 3D printing market in the light of the data found

No longer a niche technology, 3D printing is becoming increasingly popular in industries such as manufacturing, automotive, consumer goods, medical and healthcare, aerospace, and electronics.

3D printing enables the rapid and accurate creation of prototypes and finished objects of varying complexity and personalization in small batches without the need for large production capacity. Currently, the most popular types of 3D printing include FDM/FFF, which prints from thermoplastics; SLA and DLP, which print from resins selectively cured with laser or projector light; and SLS and DMLS, which form layers from plaster or metal-based powders.

According to the analysis, the global value of the 3D printing market is set to grow at a staggering rate in the coming years. A.T. Kearney estimated that the 3D printing market would grow to USD 17.2 billion in 2020 and USD 26 billion in 2021. According to McKinsey, the market will grow even faster, reaching a value of USD 100–250 billion by 2025 (Ilya Klyha, Corporate Development Analyst).

According to BIS Research, the global 3D printing market was estimated to be worth around USD 12.9 billion in 2020, growing 25% year-on-year since 2014.

In addition, the 3D printing industry recorded growth of 19.5% in 2021, valued at USD 15.4 billion. In 2021, polymer consumption in 3D printing increased by more than 40% from 2020 levels and overtook photopolymers as the most widely used 3D printing material (BIS Research, 2022).

Despite varying estimates of the size of the 3D printing market, growth trends are evident, as shown in Figure 1. There is a noticeable year-on-year increase in

the size of the global 3D printing market between 2013 and 2021, from USD 4.4 billion in 2013 to USD 21 billion in 2021.

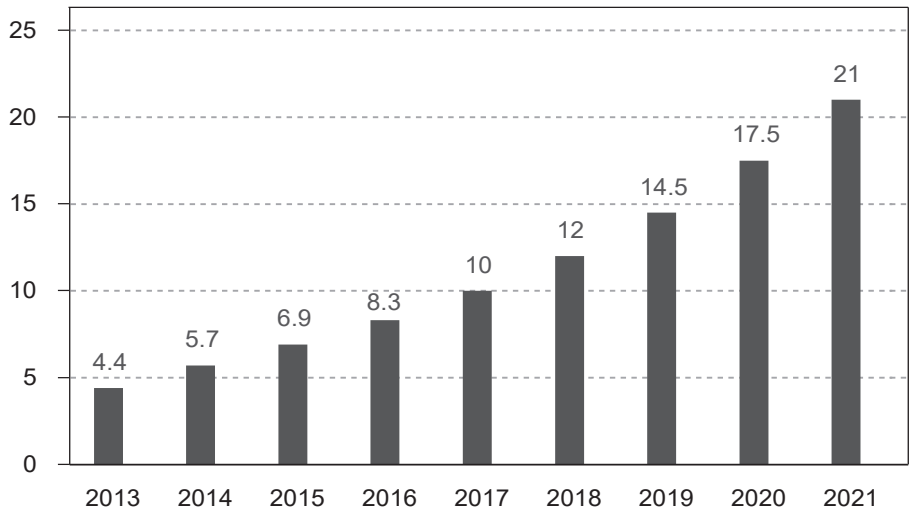

Figure 1. Global 3D printing market size from 2013 to 2021 (in USD billion)

Source: Statista, 2021.

With the expansion of 3D printing, the size of the global 3D printing materials market is also expected to grow (Figure 2).

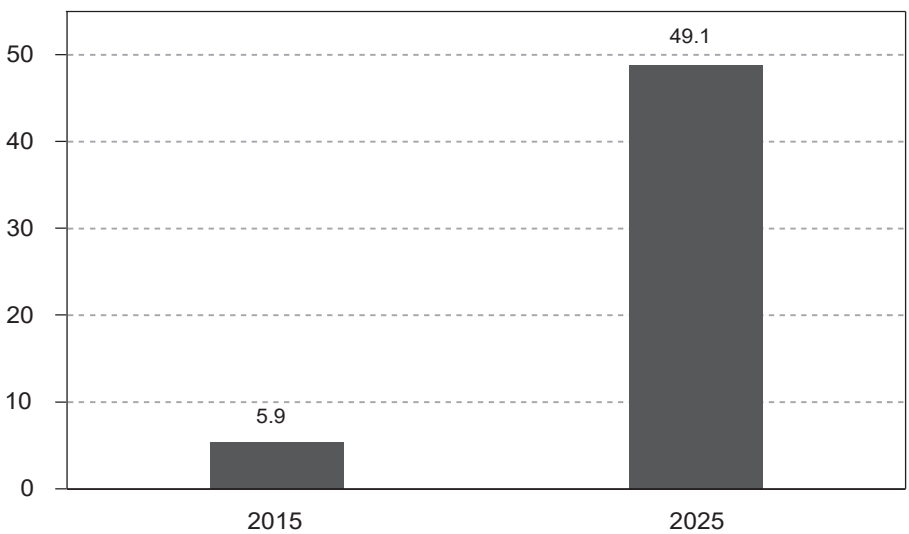

Figure 2. Forecast size of the global market for 3D printing, materials, and related services in 2015 and 2025 (USD billion)

Source: Statista, 2022.

Thus, the size of the global market for 3D printing products and services will be characterized by an upward trend over the years 2020–2026 (Figure 3).

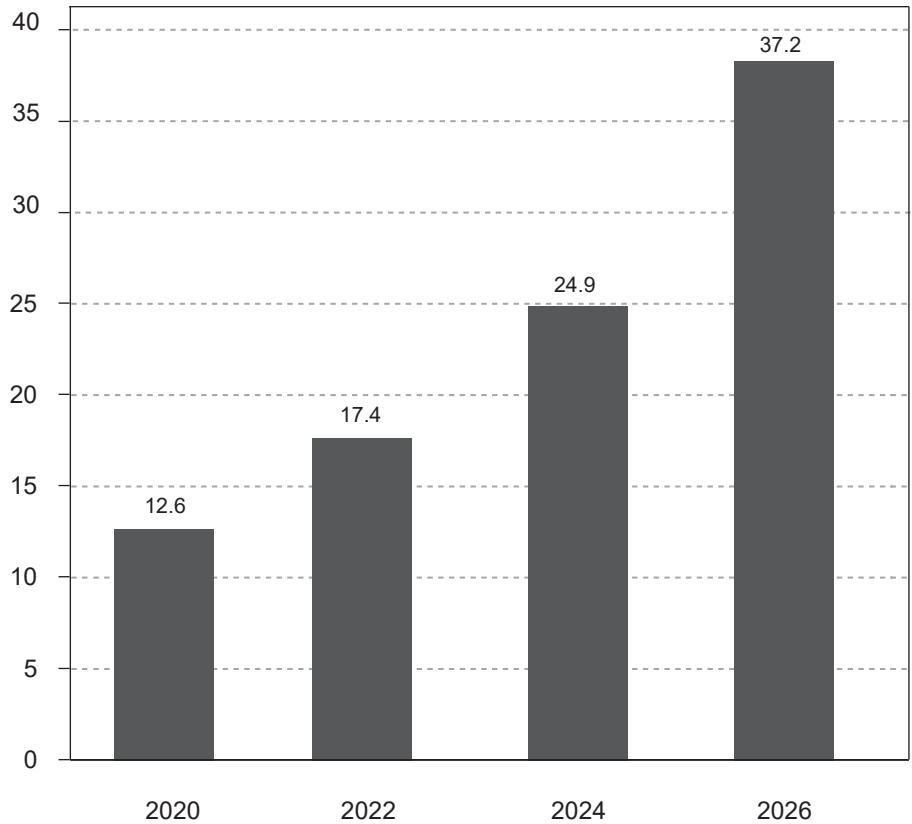

Figure 3. Global market size for 3D printing products and services from 2020 to 2026 (USD billion)

Source: Statista, 2022.

In 2023, sales of 3D printing products and services in Poland are projected to reach USD 85 million; in 2029, sales in Poland will reach USD 245.4 million (Table 1).

Sales will change by 19.7% in the following year (2023 to 2024). The compound annual growth rate will vary by 28.2% from 2024 to 2029 (Table 2).

The growth in the size of the global 3D printing market, the projected size of the worldwide printing market, and the size of the global 3D printing products and services market over the years will be influenced by the following key trends (BIS Research, 2022).

Table 1. 3D printing market sales in Poland

Year	Market sales (USD)	Share of the global market
2018	30,717.6	0.75%
2019	37,377.7	0.76%
2020	45,667.3	0.77%
2021	55,221.2	0.73%
2022	70,860.1	0.71%
2023	84,987.7	0.69%
2024	101,704.1	0.67%
2029	245,358.0	0.59%

Source: Perry/Hope Partners Global Innovation Markets Forecast (2023), p. 70.

Table 2. Compound annual growth rate in Poland (year-to-year change)

2018–2019	21.7%
2019–2020	22.2%
2020–2021	20.9%
2021–2022	28.3%
2022–2023	19.9%
2023–2024	19.7%
CAGR[1)] 2024–2029	28.2%

Note: 1) Compound annual growth rate.

Source: Perry/Hope Partners, Global Innovation Markets Forecast (2023), p. 70.

– A growing number of startups in the market. The 3D printing market is characterized by an increasing number of startups worldwide due to the highly fragmented and unorganized nature of the market. The 3D printing market comprises of hardware, software, services, and printing materials.

– The use of 3D printing for functional or end-use parts. 3D printing technology allows users to produce any part and design without compromising the quality of the final object. The number of 3D-printed functional or end-use objects is expected to increase in the next 3–5 years.

– Service providers and online 3D printing. The 3D printing services segment is one of the fastest-growing areas of the 3D printing market, and its growth is affecting the conventional manufacturing industry. Demand for online 3D printing is increasing in developed markets such as North America and Europe. The electrical and consumer goods sectors are among the leaders with the highest online manufacturing demand, accounting for nearly two-thirds of the total market for online 3D printing.

In addition to the above trends, the growth of the 3D printing market will be influenced by:

– reorganization of healthcare systems,
– industry 4.0 and in-house 3D printing,
– small-batch production,
– technology convergence.

To summarize, the 3D printing market has been characterized by a significant rate of growth and diversification in recent years. The global 3D printing market is expanding, driven by technological advances, increased applicability across industries, and demand for custom and on-demand manufacturing.

Several factors listed below are contributing to the growth of the 3D printing market.

– Opportunities for its application in various industries. 3D printing has penetrated many sectors, including aerospace, automotive, healthcare, consumer products, architecture, etc. The ability to create complex geometries, reduce material waste and enable rapid prototyping has made 3D printing an attractive manufacturing solution for many sectors.

– Customization and personalization. 3D printing enables the production of highly personalized products. This aspect has gained importance in the consumer goods industry, healthcare (e.g., patient-specific medical implants), and other sectors where customized solutions are desired.

– Cost and time savings. 3D printing can streamline manufacturing processes by reducing the need for tooling and assembly, resulting in cost and time savings. This aspect is particularly beneficial for industries such as automotive and aerospace, where complex parts and components can be produced in a single operation.

– Advances in materials. The availability of a broader range of printing materials, including metals, polymers, ceramics, and composites, has expanded the potential for 3D printing applications. Ongoing research and development of materials contribute to the growth and adoption of this technology.

It should be noted, however, that the 3D printing market is still in its infancy and there are some challenges, such as scalability to mass production, material limitations, and high initial investment costs. Nevertheless, the market still shows strong growth potential.

5. 3D printing applications in medicine

The medical and healthcare industries have seen an increase in the use of 3D printing in recent years, along with a growing number of research and development programs conducted by private and government-funded organizations. The printing of spatial elements using various materials can affect many areas of medicine and related fields, such as the pharmaceutical industry or health-related education. The

following examples show how 3D printing is being used in prevention, rehabilitation, and various therapies.

Hospitals and laboratories have invested in hardware, software, and services related to 3D printing technology. Nearly 3% of large hospitals as well as medical and research institutions already have on-site printing capabilities. They print models of the heart, to help cardiac surgeons prepare for surgery, or joint components, which are based on a natural prototype. In the next three years, one in four surgeons will prepare for surgery using 3D-printed, complete patient models (Piątek, 2018).

Along with the military and industry, medicine is one of the sectors most rapidly adopting new technologies and adapting them to its needs. This is also the case with 3D printing, which is widely used in scientific research to save lives and health.

3D printing is used to print prosthetics and implants. It is also one of the fastest-growing areas of medicine using 3D printing technology. 3D printers are used to create prosthesis components (or entire low-cost prostheses), dental implants, synthetic replacements for damaged parts of the skeletal system (such as skull fragments), or artificial heart valves. Customized prostheses can be made at a fraction of the cost and time of traditional methods. The technology also allows for iterative improvements and design modifications based on patient feedback (Lesiński, 2020).

Another area where 3D printing is being used is in rehabilitation and disability equipment. Like implants and prostheses, customized rehabilitation equipment (such as plastic-printed "armor" instead of traditional plaster casts) can significantly increase the comfort of the injured person and speed up their recovery. Thanks to this technology, it is possible to help people with disabilities with many everyday activities. For example, 3D printers are being used to create exoskeletons that allow patients with paralyzed limbs to walk independently.

3D printing is also being used to educate doctors. It enables the creation of accurate anatomical models based on patient-specific medical imaging data. These models are used for surgical planning, medical education, and patient communication. Surgeons can study and practice complex procedures on these models, improving surgical outcomes. The precise mapping based on accurate computer analysis enables creating a near-perfect preoperative model. Such a model not only helps surgeons in their work (for example, by allowing them to fit an implant on a replica rather than live during surgery), but also supports their communication with the patient and helps explain the details of the planned procedure.

The next application of this technology is the printing of tissues and organs. 3D bioprinting involves embedding living cells, biomaterials, and growth factors to create functional tissue constructs. Biogel (as a base for cell growth), stem cells, and other tissue- or organ-specific cells are used for this purpose. An auricle, urinary bladder, liver, skin, and heart or blood vessels have already been created using this method. The technology has great potential for tissue engineering and regenerative medicine. Bioprinted tissues and organs can be used for drug

testing, disease modeling, and ultimately transplantation, potentially solving the organ shortage crisis or the issue of the body's negative immune response (transplant rejection).

3D printing is being used to produce personalized medicines with precise dosages and formulations. This approach, known as 3D printed pharmaceuticals or personalized medicine, allows for customized drug delivery systems, especially for patients with unique drug needs, such as pediatric and geriatric populations.

These are just a few examples of 3D printing applications in medicine. The technology continues to evolve and has the potential to improve care, enhance surgical outcomes and drive advances in personalized medicine and regenerative therapies.

In the coming years, 3D printing may become a disruptive technology for the medical AND healthcare industry due to its diverse applications in several sub-segments. In addition, the growing popularity of AR, artificial intelligence (AI), and other advanced technologies and the mutual integration of these technologies with 3D printing are expected to create several growth opportunities for 3D printing.

Although 3D printing provides excellent benefits, it also has some disadvantages. Some of these are as follows (Ramola et al., 2018).

– Printing medicines will make them more personalized to the patient's needs, but printing a prescription with different ingredients for each patient will be very difficult. Another problem is maintaining the properties of the elements during printing, as they can change with temperature changes.

– Printing prosthetics presents challenges, such as maintaining the durability of the product. For example, they will not allow lifting heavy things and work that requires rotation of the wrist.

– Vascular organs, such as the heart and blood tissues, which have very complex structures, continue to pose problems for 3D printing.

– The incremental printing process is complicated, so a slight change in properties can change the properties of an entire cell.

– The limitation of using a 3D printed model instead of the traditional method is that it is still more expensive. In addition, the 3D models generated are still not precise enough to provide more accurate results.

– Although the 3D printer supports the preparation for surgery, there is a limitation in implementing such a method when urgent surgery is required (printing time sometimes takes several hours to several days).

6. Conclusions

3D printing is being researched, implemented, or already used in a wide range of sectors, including industrial goods, services/manufacturing, consumer goods, aeronautical/aerospace, automotive, and those related to medicine: prostheses, im-

plants, anatomical models for science, pre-surgical models, components of medical equipment and rehabilitation devices or even some medications, among others, are created this way. Work is also underway to develop prints: cells, tissues, or entire organs.

3D printing is a particularly attractive technology in cases where a "tailor-made" component is needed. For example, to reconstruct a bone fragment or to create a precise preoperative model.

Although several studies on the development of the 3D printing market and its application are available, some players are not willing to use it commercially due to the high investment required and the limited application.

Experts predict that in 50 years, biotechnology, i.e. bioprinting and 3D printing of food, will join the still-developing rapid prototyping.

The key to the development of 3D printing technology is materials and overcoming technological barriers. This mainly concerns failure-free and reliable equipment and production cycles.

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