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Medical 3D printing – the future is here

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ABSTRACT

Introduction: Continuous advances in polymer development and thriving 3D printing methods enable us to reproduce components with exceptional print precision and ensure material biocompatibility under sterile conditions. All this comes down to the fact that the resulting prints better fulfill their roles in the world of medicine and enable patients to recover faster. This precision translates into the main advantage of 3D printing, i.e. personalisation of models with perfectly reproduced structures of a given patient based on CT or MRI tests. At the same time, these prints can be used for didactic purposes by medical students from the very beginning of their professional career, which in the future will make it much easier to perform difficult and complicated operations.

Aim of the study: Presentation of the application and positive aspects of 3D printing in medicine.

Summary: 3D printing is a permanent feature on the pages of modern medicine. Thanks to it we get to know the personalized morphology of given structures, we more accurately prepare ourselves for the procedure and more often prevent probable complications, and our medical staff receives another dose of knowledge, which they translate into the profession.
Conclusions: Training on perfectly reproduced copies printed in 3D can certainly attest to the high qualifications of specialist doctors. The use of widely understood 3D printing technique in medicine is slowly becoming commonplace.

INTRODUCTION

The dynamic development of technology definitely imposes the pace of development in the field of medicine[1]. The most innovative way of manufacturing various objects - spatial printing presents extremely high potential, providing the production of three-dimensional objects based on digital data by overlapping a given material layer by layer. Other names of this process found in literature are fast prototyping or additive manufacturing (AM) [1].
Nowadays, with the use of 3D printers we can print almost anything, from small, simple objects (e.g. plastic forms), through toys, clothes even to such complicated structures as rockets or houses. All of this, of course, is made possible by the progressive precision of the production process. Continuous research and analysis in the field of three-dimensional production technology makes it more and more biocompatible. This has opened up a number of new possibilities for its use in medicine. More and more often 3D printing is used in healthcare, playing an important role in planning surgeries or training young doctors. Taking into account the dynamics of technology development, it can be assumed that the prospect of printing whole organs in the near future is quite real [2].

HISTORY OF 3D PRINTING IN MEDICINE

3D printing technique was developed by Charles Hull in 1984 [3]. Since then, his patent has been used in many branches of the world economy. The development of technologies and processes has led to the deepening of the use and application of AM, which has made a reduction in the cost of purchasing and using 3D printers, and this technology has also become available to amateurs and hobbyists [4].
In medicine, computed tomography (CT) has been used for many years for computer-aided design (CAD), which allows the creation of three-dimensional, virtual models of patient body.

As a result, the problem faced by many - namely the fact that modelling and support complex software - was solved in this field, which allowed for a quick implementation of 3D printing technology in medicine, which was surprising even for Hull [4].

The precursor to the introduction of 3D printing for medical use was a team of doctors from Harvard Medical School, who manually performed a fully functional urinary bladder replacement by creating a synthetic scaffold from collagen and polymer and putting it on the cells of patients until the finished organ was grown. Unfortunately, manual production was too much time-consuming and cumbersome [3].

The key event was the automation of this process by Dr. Anthony Atala. In 2004, he took over the Wake Forest Institute for Regenerative Medicine (WFIRM). Together with a team of scientists, they developed machines that made it possible to print the scaffolding biocompatibly. Then they successfully conducted small clinical trials in which they implanted manufactured tissues and organs into patients [4].

Scaffolding quickly found its application in other specialties, mainly in orthopedics, where the essence was to create biologically reproduced structures. The use of 3D printing in orthopedic procedures is a daily occurrence today [4].

However, what we are striving for is a fully functional bio-print. In 2013, full cellular liver tissue was printed. The Organovo company from the USA, which carried out this project, showed how great the possibilities of bio-printing are by reproducing the biology of the human body [4]. There is no doubt, therefore, that nowadays, one of the greatest enthusiasts of 3D printing is doctors, medical researchers or even patients themselves [2].

Today, almost everything from toys to complex machines and components is created using 3D printing. By reducing assembly costs by printing finished, connected components, it is possible to test innovative ideas through production iteration in a short period of time [5].

STATE OF KNOWLEDGE

What is 3D printing?

3D printing is a mechanical process of creating objects by successively overlapping layers of print, up to the creation of a computer copy of the model. Therefore, 3D printing can be called a bridge between digital 3D models and their physical representation in reality. [2]

The materials used in spatial prints are:

- Resins
- Metal alloys
- Titanium

- Polymers
- Biodegradable materials
- Ceramics
- Composites.

Taking full advantage of the possibilities offered by computer hardware and software - design and scanning of objects makes it possible to create a large number of structures, almost from any material, of any shape and size in a short period of time, thanks to the flexibility of the 3D printing process. It can take just a few hours to create a given object from scratch [5]. It also enables highly personalized spatial prints, which is crucial e.g. in the situation of improving prototypes [2].

The manufactured spatial objects are characterized by unprecedented precision, which leads to the fact that they are used, among others, in medicine. The biggest advantage is the fact that it is a "tailor-made medical product". They can be e.g. prosthetic limbs, bones, teeth, implants or blood vessels, but they must be biocompatible.

3D printing techniques

There are many types of 3D printing, the most important of which are:

1. *SLA* - *Stereolithography* - cures printed 2D liquid polymer layers with UV light. This process is repeated until the entire printout is complete. Thanks to this technology, prints are detailed and smoothly finished, but there are colour limitations - usually single-colour models. The advantageislowcost [6,7].
2. FDM - fused deposition melting - this method uses a thermoplastic filament melted in the nozzle and applied to the printer table in a specific configuration. The nozzle must be heated to a temperature higher than the glass-transition temperature of the fibre. This is a fairly popular and easily accessible method in the consumer market, providing many thermoplastic properties including flexible materials. However, the resulting prints often require processing, as their resolution is quite low. The advantageisverylowmaterialcosts. [6, 7]
3. SLS/SLM - selective laser sintering/selective laser melting - consists in selective sintering/melting of finely powdered polymer applied evenly on the work table with the laser. Biocompatible materials as well as high strength raw materials and metallic alloys have been adapted to this technology. The costs of this method are quite high, and the final printout requires the necessary processing[6, 7].

4. Inkjet printing - this process uses powdered raw material similarly to SLS, distributing it on a working platform and then, similarly to traditional 2D inkjet printers, the printhead applies fine droplets of binding resin. The advantage of this method is a high fidelity multi-colour print, but the material properties are limited and the surface finish is granular [7].

5. Bioprinting - where biomaterials/biotches containing living cells (e.g. from culture) are used for production [6,7].

6. PolyJet Technology - a versatile process that combines inkjet and SLA printing to create a liquid photopolymer on the work table, which is then cured using UV light. With this method, a smooth finish and high resolution printing can be achieved. They can also be multi-coloured and made of many materials with variable properties. However, this is an expensive method and is additionally limited in terms of biocompatible printing [7].

Bioprinting. Biocompatibility of materials

All biotechnology focuses on the analysis of development, tissue regeneration process and how to design its in vitro reconstruction process. The dynamically developing tissue engineering for nearly 40 years has been aimed at creating biological substitutes that will improve the functions of tissues or restore them. The range of materials for biological scaffolding and cells is constantly being extended. It is very important that the materials used for medical 3D printing are biocompatible, which according to the definition means "capable of correct tissue contact behaviour in a specific application" [8].

The European Society for Biomaterials defines biomaterial as 'any substance other than a medicine or a combination of natural or synthetic substances that can be used at any time to supplement, replace or perform the function of organ tissues or parts of organs' [9].

The flexibility of spatial printing allows scientists to create devices and structures used in medicine with a wide range of physical and biological properties. In addition, all of this can be done remotely [2]. All this is essential in tissue engineering, where the scaffolding must provide the organ produced with the right structural conditions for macro, micro and nano-architecture [10].

Macroarchitecture is based on the anatomical features of the patient and it is, for example, the general shape of the organ. Microarchitecture is responsible for the architecture of tissues building the organ (e.g. cell distribution in space, number and size of pores or their connection). Nanoarchitecture is a modification of cell surface what enables their adhesion, proliferation or differentiation [10].

The bioprinting allows to reproduce anatomical differences of a given individual and reconstruct organs with a complicated structure (e.g. liver) [10]. This process will initiate a new chapter in transplantology, where it will not be necessary to wait for an organ donor, but only print the appropriate organ from the patient's own cells.

However, apart from the construction of biocompatible scaffolds placed in growth and differentiation factors and then blown up with stem cells, it is important to remember about proper vascularisation and ensuring strong growth and differentiation of cells in order to make the organ fully functional.

An equally important aspect may be the study of the influence and toxicity of drugs on a given organism by printing personalized microcosms of organs planted with cells on an in vitro medium containing specific substances. Such tests can be very useful for screening drugs and thanks to them it is not necessary to conduct them in vivo on patients[2].

3D PRINTING - APPLICATION IN MEDICINE

Training models for students and young doctors

Learning anatomy is something that every medical student encounters at the beginning of his or her education in this field. It is a kind of introduction to the medical world and at the same time the foundation of medicine. For many, the beginnings are difficult, because of the advanced structure of the human body and the multitude of structures. Education is often based on assimilation of theories from books, photos or diagrams, but visual knowledge of the given structures significantly broadens our knowledge and imagination, so that our competences become more practical. The use of human remains by both educated medical staff and students has always been a controversial issue. Nowadays, having modern possibilities of medical imaging, on the basis of many analyses of anatomical structures a printout can be created which perfectly reflects the real appearance of anatomical structure. Particularly noteworthy is the example of the skull - bone structure, which, due to its very detailed and complex structure, causes the students the most problems in learning to pass the exams. Accuracy and accessibility of spatial prints allows for easy and simple creation of many copies of a given structure of any size, so that the needs of medical education are fully satisfied, and in addition, cultural aspects and ethics are not violated.

Young medical doctors finishing their studies focus their future on a given medical specialization. Because of the many classes in college, there is not always a chance to see or assist in a given operation. It is known that the time of specialization training is to learn, but the lack of familiarity with the equipment, operating room and small professional experience increases the risk of complications or extends the duration of surgery, thereby increasing costs. There are also rare cases where it is worth being prepared for. Just such preparation and familiarity offers us a wide range of possibilities for spatial printing. Having specially prepared training during specialization, where it is possible to perform simulations of the procedure on a properly prepared model of a given case will definitely better prepare us for various situations, often unexpected, so that it will be easier for us to focus and precisely perform the procedure, previously performed on a three-dimensional model.

Pre-operational models:

Pre-operative planning of hearing implant placement in complicated cases

For conductive or mixed hearing loss, while standard hearing aids cannot be used (due to microcirculation loss or surgery of the middle ear or mastoid process), bone conduction hearing aids that are anchored in the bone must be used. An example is BoneBridge (BB, MED-EL, Innsbruck, Austria), which is an active implant that does not suppress sound passing through soft tissue. The main challenge during implantation is to place the implant with high accuracy. Therefore, when planning such an operation, as shown in the studies, the spatial printing of temporal bone on the basis of ear CT scans has been shown to be beneficial. Specialists who had such models could precisely plan the access to the operated area and the place where to drill [11].

Transthoracic simulation of ear endoscopic surgery

Transcanal Endoscopic Ear Surgery (TEES) as a relative new procedure forces surgeons to learn new techniques of operation - endoscopy in one hand and instruments in the other. The aim is to implement endoscopic postoperative controls as the gold standard wherever possible as a method with higher sensitivity, lower invasiveness and shorter hospitalisation times. 3D models were made in computer-aided software using anatomical measurements carried out in anthropometric examinations of the external auditory canal. The middle ear's working area is based on a grid created by serially joining vectors from the external auditory canal sections. The TEES simulation spatial printout was properly designed and printed from materials that can withstand the simulated operation with endoscopic equipment. Practicing specialists agreed that this practice increases the level of training and improves the time of performing the procedure, which makes it a highly fidelity surgical simulation. However, it should be remembered that it takes a long practice to learn how to perform the procedure in parts. This is a much cheaper and more accessible technique than training on deceased donors. It allows trained doctors to quickly understand the detailed course of the folds in the outer ear canal [12].

Injection laryngoplasty – paralyzed vocal fold

An extremely difficult clinical condition for both the patient suffering from it and the otolaryngologist is the phonation failure of the glottis, which is a consequence of the paralysis of vocal folds. What is worse, the etiology of this pathology is most often iatrogenic - the damage occurs during surgical procedures. Surgical treatment is based mainly on the use of one of two methods: medializationthyroplasty and injection laryngoplasty, during which a substance is injected into the vocal folds, which aims to restore the conditions allowing the creation of a properly sound voice at the level of the glottis. This method poses a number of challenges for clinicians: choice of the way of injection, choice of the substance to be injected, proper injection site, as well as the number of injections themselves. 3D printing technology can help here. Complicated anatomy of paralized cord was possible to recognize by 893 scans, it was also possible to accurately compare the paralyzed side to the normal side, both during phonation and breathing. The three-dimensional volumetric measurements allowed the researchers to estimate the correct amount of material needed for injection [13].

This study also enabled scientists to investigate vocal folds accurately. By performing a simulation on a 3D printed model, it was possible to find out which place was the most suitable for inserting the needle, how deep it should be done, and how the tools should be directed during the procedure [13].

Already used 3D printouts:

Nasal septal perforation

Spatially printed reconstructive nasal septum prostheses are mainly used for the treatment of large or irregular septal perforations or for intolerance of general anaesthesia or antithrombotic drug users. There are many reasons for perforation of the nasal septum - from external injuries, vasculitis or previous surgical procedures in this area. They may have serious consequences, and may significantly reduce the quality of life of the patient, causing, for example breathing difficulties, pain, the formation of scabs in the nose and others. From the CT data we illustrate the perforated septum of a given patient together with adjacent tissues and print a 3D model based on which the prosthetists create a prosthesis. In the case of complications such as septum curvature, so that the side wall is very close to the septum, the surgeon performs simulations to improve the model and provide larger margins. The sterilized prosthesis is inserted through the nostrils of the patients. In order to implement it easily, it is necessary to bend the upper left and lower edge towards each other using seams. The nasal mucosa is then anaesthetized locally. In addition, an endoscope can be used for the placement of large prosthesis. The prosthesis is needed to be inserted surgically when it is much larger than the diameter of the nostrils or when, for example, sinus surgery is necessary. Advances in technology, both in design and in hardware improvements, have led to a more precise prosthesis that is better suited and more comfortable for the patient. Successful closure of perforation of the nasal septum, surgical or prosthetic septum, usually significantly improves the patient's condition and reduces the symptoms specific to the disease [14].

SUMMARY

3D printing is a permanent feature on the pages of modern medicine. Thanks to it we get to know the personalized morphology of given structures, we more accurately prepare ourselves for the procedure and more often prevent probable complications, and our medical staff receives another dose of knowledge, which they translate into the profession.

It is cheaper and faster to improve the qualifications of the medical staff by means of perfectly reproduced structures from 3D printers in all areas of medicine.

Additionally, 3D printout models can help patients in recognizing their own health issues and educate family members on patient health issues.

The above work includes examples of spatial printouts used mainly in otorhinolaryngology, but they are also used in specializations such as orthopaedics, surgery, cardiology and many others.

CONCLUSIONS

3D printing is definitely an innovative method both in planning complex surgical operations and in medical science. Models based on the patient's anatomy certainly increase the precision of operations and thus reduce complications. Moreover, they shorten the time of planning the data of procedures and reduce the costs associated with them.

Training on perfectly reproduced copies printed in 3D can certainly attest to the high qualifications of specialist doctors. The use of widely understood 3D printing technique in medicine is slowly becoming commonplace.

Further development and progress in 3D printing, as well as increased availability of materials and printers will contribute to the removal of "intermediate steps" and we will be able to directly print medical prostheses, tissue skeletons and even 3D stem cells and tissues.

It is clear that this is a better future. The future that is here.

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