3D models lead a revolution

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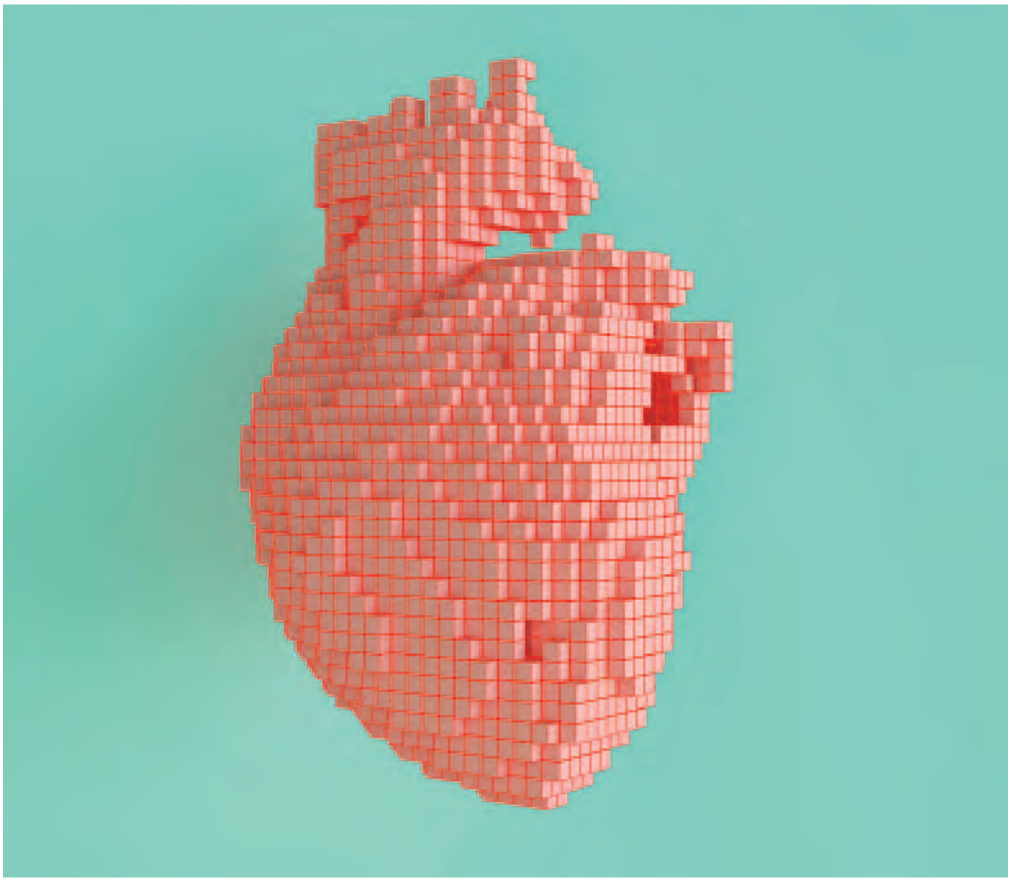

Abstract

Three-dimensional (3D) printing is revolutionising healthcare as we know it. The technology involves taking a digital model of a subject and printing it in consecutive layers to create a fully formed object in the form of a 3D model. Diseased organs can be modelled and reproduced, allowing surgeons to handle and examine them before, during, or after an operation. The ability to prepare for surgery with this direct, hands-on approach has improved outcomes around cost, speed, and precision. In addition, the ability to view pathological diseases tangibly is invaluable for patients' understanding of diseases, thereby improving the overall patient-doctor relationship. Likewise, medical students can further their understanding of complex human anatomy and deepen their knowledge of pathology. The technology is also a large contributor to precision medicine, through its ability to create prosthetic designs suitable for patients' unique aesthetic and functional needs. Furthermore, the 'polypill', a product of 3D printing, can package multiple complex medications into a single tablet – a promising tool for addressing the challenges of polypharmacy. Despite the notable applications developed thus far, 3D printing has not yet reached the limit of its vast capabilities. With the increased implementation of the technology within the healthcare sector, additional efforts and research towards enhancements will allow us to realise the full potential of 3D models.

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Introduction

Each year, the healthcare industry continues to make leaps and bounds towards greater achievements. Three-dimensional (3D) printing, an up-and-coming technology with highly versatile societal applications, has captivated the medical community as a rapidly expanding medical tool with the potential to revolutionise healthcare.

Though it is called 3D 'printing', the technology itself does not involve any ink, but rather utilises materials such as plastics or living cells.[1] This is done through the process of additive manufacturing, where a software directs hardware to deposit material in successive layers until a fully formed 3D model has been created.

Although one may think of 3D printing as a recent technology, its history begins in 1981 with a Japanese doctor's patent application for a 3D printer. Unfortunately, Dr Hideo Kodama's application was not successful and, as such, it was not until 1986 that the first patent was granted to an American inventor named Charles Hull. This led to the creation of the first 3D printing company: 3D Systems. Today, 3D Systems is one of the largest 3D printing companies and a leader in 3D printing innovation. Even Hull himself admits that he underestimated the impact and potential of this technology.[2]

Since then, there have been major improvements in both imaging and printing that have led to further reductions in cost, making 3D printing technology attractive to multiple fields.[3]

Its impact on medicine has been compared with the revolutionary role of computerised tomography (CT) scans in the 1970s, which served as a ground-breaking substitute for exploratory invasive procedures.[4] While a CT scan will produce hundreds of images at once that subsequently need to be reviewed, 3D technology allows cross-sectional slices to be combined into a concise 3D representation of the area being scanned, allowing for greater accuracy compared to the commercially available two-dimensional displays.[5]

3D printing in healthcare is allowing medical professionals to offer patients new diagnostic and management strategies, especially when used concurrently with medical imaging.[6]

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Uses of 3D printing

Optimising surgical planning

Even before a surgery takes place, 3D printing technology is making significant changes in the way surgeons think about procedures and the technical challenges that they may encounter. There have been many publications regarding tissue replicas being used as a supplement to scans from traditional imaging modalities in preoperative surgical planning.[7-10] This has been particularly helpful in patients with unique anatomies where the 3D print can be used as a visual aid and a printed record of the original anatomy, such as in children who require complex surgeries due to anatomic anomalies.[8,9]

The first step in generating a 3D object is acquiring the image data from traditional imaging modalities. The quality of the image is important as low-resolution images can result in discrepancies between the generated model and the patient's actual anatomy.[11] Following this, the region of interest is extracted through a process called 'segmentation'. The data is then transformed into a format recognised by the 3D printer, and is subsequently printed.[12,13]

These patient-specific organ replicas can allow surgeons and trainees to familiarise themselves with the patient's unique anatomy, contributing to the emerging model of personalised medicine. This has the potential benefit of reducing operating time and risk of trauma to the patient.[11] The reduction in operative times is important to note as this has led to overall cost reduction attributed to using the technology.[14] In a study examining the use of 3D printing in orthopaedic surgical planning, the researchers observed a decrease in bleeding (average decrease of 50%) and a decrease in surgical time in all cases (mean time decreased by 43%), which consequently resulted in a reduction in the amount of anaesthesia required. Furthermore, once the models were examined by the surgeons, decisions were made to opt for a different surgical strategy for some patients than what is normally done to reduce the risk and the number of operations.[6]

The models used for preoperative planning can also be used intraoperatively. 3D models can be colour coded to highlight certain areas of pathology that a surgeon may want to either excise or avoid during surgery.[15] This function may help to orient surgeons during the operation, thereby minimising damage to surrounding healthy tissues and reducing error.[5]

In conjunction with the aforementioned advantages to the surgeons, patients themselves can also benefit directly from 3D printing. The use of pre- and postoperative surgical models can increase patients' understanding of their upcoming procedures.[11] Studies have shown that when physicians used a 3D model to explain a procedure, patients and their families had an increased understanding of the aims

and possible complications, resulting in greater patient satisfaction.[15,16]

The list of surgical specialties that have been enhanced by 3D printing is an expanding one. In 2012, surgeons from the Cardiovascular Division of the University of Wisconsin School of Medicine turned to 3D printing to print out a scaled replica of a heart containing a left ventricle pseudoaneurysm, a complication of myocardial infarction carrying an increased risk of mortality.[17] Using the 3D model, surgeons were able to determine the best approach to cannulate the aneurysm, and select the appropriate shape and size of the catheter and occlusion device to be used specifically for this patient's dimensions. With guidance from the 3D model, percutaneous closure of the pseudoaneurysm was successful.

In 2015, surgeons from the Children's Hospital of Fudan University in Shanghai used 3D printing to create a scaled replica of conjoined twins with a shared digestive tract.[18] The model served as an accurate representation of the complicated anatomical structures and anomalies that would be encountered during the operative separation. This allowed surgeons to practice alternative techniques to determine the safest way to proceed.[18]

Educating future doctors

Understanding gross anatomy requires complex spatial awareness. A thorough understanding of 3D anatomic relationships is vital to the interpretation of imaging studies, the safe and effective execution of surgical procedures, and the prompt arrival at accurate diagnoses.[19] Human anatomy has traditionally been taught using cadaver dissection, where students gain understanding through direct visualisation and manipulation of the 3D structures of their cadavers; however, 3D models may prove to be more advantageous due to superior cost–benefit ratios, easier storage, and the ability to display rare diseases through intricate 3D replications.[20] Furthermore, the specific organ positioning displayed through this technology is a closer representation of what may be encountered in the operating room compared to the fixed tissue of cadavers, and would facilitate the depiction of structures that could have been damaged during cadaver preparation.[21]

> ***There have been many publications regarding tissue replicas being used as a supplement to scans from traditional imaging modalities in preoperative surgical planning.***

A randomised controlled trial examined medical students' understanding of complex spinal anatomy using teaching modules across three different formats: CT images, 3D images, or 3D-printed models.[22] The result of the chi-squared analysis showed that those with exposure to 3D-printed models were more confident with the material and had a deeper understanding of the mechanisms of disease compared to students trained using the other two mediums ($p<0.05$). The ability to manipulate physical models allowed for a more wholesome understanding of anatomic relationships and showed superior educational benefit compared to cadaver dissections.[13,23,24]

Additionally, medical students can ease their way into their clerkship years by practicing invasive procedures on 3D models rather than the traditional method of 'see one, do one'. By providing a 3D model for

teaching and practicing a complicated spinal procedure, such as a lumbar puncture, the risk of injury to actual patients can be reduced.[25] In a study examining the impact of 3D models on the understanding of congenital heart disease within residents, there was added benefit among those in the interventional group, particularly regarding complex anatomical conditions such as Tetralogy of Fallot.[26] 3D models appear to be an efficacious adjunct to traditional cadaveric teaching and a valuable tool for medical students in both their lecture-based and early clinical years.[27]

Innovations

3D printing has influenced many aspects of healthcare, providing novel opportunities to create or enhance the function of various innovations across multiple fields. With the introduction of 3D printing, prosthetic limbs have gained increased symbiosis with patient uniqueness. 3D printing allows for the design of comfortable and cost-effective prostheses that can suit a patient's specific body type.[28] Importantly, the advantages of such technology are not bound by borders or socioeconomic status. Low-cost 3D printers are being used in war-torn developing countries to make prosthetics for amputees, such as in Sudan where there are an estimated 50,000 patients in need.[29] The United States Army also aims to implement 3D printing by first imaging all their soldiers in a healthy state, so that in the case of an amputation, they can reconstruct the prosthesis in the field.[30]

Areas that are under blockade often have trouble accessing basic medical supplies and likely depend on overseas shipments for their materials. Obtaining medical devices with 3D printing or placing a 3D printer directly in the area of need can provide immediate access to critical supplies. Dr Tarek Loubani, an Associate Professor at the University of Western Ontario, was working in the Gaza Strip during times of hostility when there was a shortage of medical supplies due to a long-standing blockade. Dr Loubani's solution included utilising 3D printing technology to create supplies such as stethoscopes, for as little as 30 cents.[31] Having almost immediate access to scarce medical supplies in war-ridden regions can help to ensure that victims receive a level of care that is not limited by a lack of basic supplies.

Additionally, the 3D printing technology facilitates the creation of artificial tissue with the use of living cells, as opposed to traditional synthetic agents.[32] These tissues may be used for medical research, as they are miniature replicas of organs, or as cheaper alternatives to human organ transplants.[33]

The use of 3D printing in transplant surgery addresses most moral and ethical issues that may be tied to traditional transplant methods. Additionally, 3D printing decreases the risk of tissue rejection, as customised organ development utilises the patients' cells; however, the revascularisation of tissue remains a challenge.[34] NASA is offering a $500,000 prize for the first research team that can establish 1cm thick human vascularised organ tissue in an *in-vitro* environment, that can maintain metabolic function similar to their *in-vivo* native cells throughout a 30-calendar-day survival period.[35]

Moreover, 3D printing has the potential to change the pharmaceutical world and simplify daily life for patients with multiple ailments and complex drug regimens through the creation of a unique pill that can hold multiple drugs at once, each one with different release times.[36]

This has already been done with the so-called 'polypill', which demonstrates that complex medication regimes can be combined into a single personalised tablet.[36] The pill is designed in such a way that there are several compartments, each one with a drug that requires a specific release time. Distinct release profiles were made possible by utilising various material compositions that altered drug distribution and diffusion when placed in solutions.[37] In addition to enhanced pharmacokinetics and pharmacodynamics, 3D-printed pills in the polypill concept can be highly cost effective, thereby making the technology accessible to poorer developing countries and applicable to health programmes at an affordable price.

The future of 3D printing

Dr Frank Rybicki, a leading American expert in the applications of 3D printing in medicine, has been recruited as chief of medical imaging at The Ottawa Hospital to direct the hospital's implementation of 3D printing technology.

Part of his role is to speak out publicly to share the realities and potentials of such technology with members of the public and healthcare workers. As he is from the United States, where 3D printing has been expanding most, he is certain that the widespread acceptance of this "ultimate form of personalised medicine" is currently underway, and it is merely a matter of time before it becomes the standard in radiology departments across the country.[38] As 3D printing becomes more widely available, opportunities for innovation will continue to arise. In the field of orthopaedics, 3D-printed casts are being developed. The aim is to create an injury-localised exoskeleton, with denser material focused on the fractured area for more support and a well-ventilated, lightweight structure designed for patient comfort.[39] In addition, further innovations are being considered as scientists are developing four-dimensional (4D) printing methods derived from 3D-printed models, with the added ability to change shape once printed.[40] Interestingly, such technology would have applications in wound treatment, as the 4D-printed structures can be seeded in with living cells. The future of this technology depends on further research, awareness of the boundless potential, and leadership dedicated to implementing programmes within a clinical setting.

Conclusion

Technology drives innovation in healthcare, from CT scans to anaesthetics to antibiotics, and these advancements have made significant improvements to the practice of medicine. 3D printing is a technological innovation that is transforming healthcare by assisting medical students, residents, physicians, and surgeons in a variety of ways. Medical training programmes could avail of 3D modelling to improve anatomy teaching and allow students to have a more hands-on approach.

Physicians can utilise these models to explain disease pathophysiology to patients, and this enhanced understanding may empower patients to ask specific questions about their health. Additionally, surgeons can use 3D-printed patient-specific organ replicas to simulate procedures as part of postgraduate surgical training and preoperative complex surgical planning.

We have also seen that this technology is not confined to developed countries.

The applications of 3D printing in the field of medicine are nearly limitless, and it is indeed a promising field that mandates further exploration. 3D printing is paving the way for a universally enhanced approach to healthcare due to improved patient satisfaction and comprehension, enhanced surgical planning, and greater savings to the healthcare system.

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