3D PRINTING IN HEALTHCARE: IMPLICATIONS ACROSS VARIOUS MEDICAL SPECIALTIES

by

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3D printing in healthcare: implications across various medical specialties

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Abstract

This paper provides a systematic review of the current uses of three-dimensional (3D) printing in healthcare with a summary of subsequent findings. Research was conducted online using specific terms and the resulting articles were sorted and categorized. There are several current uses of 3D printing in healthcare that currently overlap different medical specialties. There are also several possibilities for cross-utilization in different medical specialties using 3D printing as the technology matures.

Keywords: 3D printing, three-dimensional printing, healthcare, health, medical

Introduction

Three-dimensional printing (3D) has emerged as a viable way to produce prototypes for industrial purposes and can easily be adapted to healthcare applications. In addition to allowing rapid prototyping for medical devices, it allows for planning complicated medical procedures using an exact replica of the affected area or organ of the patient. 3D printing also allows medical students to learn from hands-on experience without the need for invasive medical procedures. Additive manufacturing technology began over 40 years ago and the patent for Stereolithography printing was submitted in 1986 by Charles Hull. Other types of 3D printing were patented several years later (Shaheen et al., 2022).

3D printing is slowly making its way into healthcare and there is a huge number of potential applications for it across different medical specialties. Currently radiology is one of the primary medical specialties utilizing 3D printing technologies. Printing a replica of a patient's affected area (spine, heart, brain, etc.) allows the radiologists and surgeons a better overview of the spread of the disease and the complexity of any necessary surgery (Reeves, 2023). However, there are other uses of 3D printing in healthcare that are being explored independently. They could all benefit from being brought together to share expertise and experience as the use of 3D printing in healthcare grows.

The purpose of this paper is to research and determine the current uses of three-dimensional (3D) printing in healthcare. This will help identify any overlap between different healthcare areas where the technology can be utilized in different ways for different specialties (e.g., cardiac surgery versus otorhinolaryngology surgery) and help reduce wasted time as different disciplines implement 3D printing into their techniques. Current research into uses of 3D printing in healthcare include biopolymers, bone tissue engineering, treatment of congenital heart disease, drug manufacturing, hip and knee arthroplasty, otorhinolaryngology (ear, nose, and throat) and treatment of pelvic fractures. Another area of healthcare that can benefit from 3D printing is replacement organs for transplantation as there is a shortage of kidneys in India due to various cultural and religious beliefs (Bruzzone, 2008); being able to print a replacement organ using the recipient's DNA would significantly the chances of rejection (Karandikar et al., 2020). This research will answer the following question:

RQ1: *What are the key findings that emerge from the literature regarding 3D printing in healthcare?*

The findings of this study will reveal the overlap between current 3D printing uses in healthcare and how those can be utilized for more effective application amongst different disciplines.

Literature Review

This literature review examines the current usage of 3D printing in healthcare including biopolymers for custom-printed mesh, bone tissue replacement using biominerals or coffee grounds, printing of custom medications for pediatric patients, and nasal implants. It also examines the possible overlaps that could help expand the usage of 3D printing for heart disease, arthroplasty, ear, nose, and throat surgery, dentistry, and prototyping. By combining all the research into a single paper, this author hopes that 3D printing can gain more acceptance and use in healthcare.

Biopolymers

One potential application for 3D printing in healthcare, according to Domínguez-Robles et al. (2019), is the use of biopolymers to allow healthcare providers (doctors, hospitals, and surgeons) the ability to print custom mesh for patients. By incorporating antimicrobial materials into the mesh mixture, the biodegradable mesh would assist in wound healing while preventing infections. The mesh would be customized for each patient, which would reduce waste from one-size-fits-all mesh and could be customized to dispense different medications throughout the healing process.

Bone Tissue Engineering

Tissue Engineering, an alternative to bone transplantation, aims to maintain, restore, and enhance the function of injured organs by developing substitutes from organic materials. Bone tissue engineering is a new scheme intended to help promote the growth of new bone, eliminating the need for transplants. Testing five biominerals (eggshell, pearl, turtle shell, de-gelatinated deer antler, and cuttlebone) by creating scaffolds, the authors were able to determine the best mixture, printer settings, and scaffold size for each of the five biominerals and that there is good compatibility between those biominerals and bone regeneration (Gang et al., 2022).

PLA/Coffee Grounds Composite

Yu et al. (2023) determined that incorporating coffee grounds into pulverized polylactic acid (PLA) powder at a 3% ratio produces higher-quality printing material. The PLA produced in this manner exhibited higher tensile strength and better elasticity than unmodified PLA. PLA produced in this way could be incorporated into 3D-printed dental work to help color-match the patient's teeth. In addition, coffee grounds could be mixed in with the 3D-printed medications to provide a pleasant flavor for patients when swallowing of the pills.

Congenital Heart Disease

The ability to view a patient's cardiac structure is of great importance in diagnosing congenital heart disease. In the study by Liang et al. (2022), the ability to 3D print their subjects' blood pool and myocardium allowed for improvements in the diagnostic accuracy and timing of congenital heart disease by medical students, experienced sonographers, and experienced cardiac surgeons. 3D printing the models of each patient allowed medical professionals to get a better view versus traditional 2D imaging (CT scans) without requiring invasive surgery on the patient.

Drug Manufacturing

3D-printed medication would usher in a new era of healthcare as it would allow for compounded, customizable pills for individual patients that could be printed on-site. In addition to compounding multiple medications into one pill, preventing patients from forgetting to take medications, this would allow customization of each patient's medication's composition, dosage, shape, and size. This would aid in preventing accidental overdoses, confusing medications between patients, and helping with the inability to swallow medications (Andreadis et al., 2022).

Concerns about 3D-printed medication

According to Goh et al. (2022), concerns held by administrative and medical staff include quality control and assurance, medication identification, and regulatory issues with governments. Another obstacle that will have to be overcome is where to place the 3D printers that can produce the medications. Several possibilities were explored by Andreadis et al. (2022) including patient's homes, small pharmacies, and hospital pharmacies. Each placement has different benefits and drawbacks and requires significant infrastructure and security investment.

3D printing with gelatin-carrageenan gel for children's medication

Carrageenan is a commonly used ingredient in food production created from red seaweed. A major shortcoming in pediatric medicine is drug-related due to the differences in administration, dosage, and tolerance. This could be alleviated by 3D printing medication specific to each pediatric patient using carrageenan gel combined with gelatin. Based on results from testing seven formulas, Liang et al. (2023) were able to determine the optimal mix to create a printable pill that is chewable and easily dissolves with 85% efficiency.

Hip and Knee Arthroplasty

The need for a more effective method to perform total hip and knee replacements has led to digital orthopedics technology that uses computed tomography (CT) scans to 3D print a patient's joint. This allows for more accurate diagnosis and understanding of the injury, simulation of the injury to create a course of treatment, more involvement of the patient in the treatment plan, and better prosthetic implants. In addition, the use of 3D-printed implants decreased the number of infections or other complications experienced by the patients in the study, which decreased their medical costs and recovery time (Zhang et al. 2021).

Materials

According to Kholgh Eshkalak et al. (2020) there are a multitude of materials that are viable in 3D printing usage for medical purposes. Metals are most suited for orthopedics due to their high strength and easy fabrication. Ceramics are suitable for dental implants, and some orthopedic implants require active usage, due to biocompatibility but are harder to manufacture. Polymers are biodegradable and easily molded to fit but can react to bodily fluids and are difficult to sterilize. Lastly, composites are corrosive resistant but expensive and laborious to manufacture.

Neonatal and pediatrics

Another area where 3D printed models provide a significant positive impact is in neonatal and pediatric care. Due to the complexity of patient anatomy due to the differing sizes of organs, surgical planning is more complicated in this field. 3D printing models allow surgeons to prepare using a better representation of the patient than 2D images alone. In addition, 3D printing allows for customization of medical equipment to fit children more accurately which increases the efficacy of treatment and allows for immediate

adjustment of prosthetics as the child ages and grows. Lastly, 3D-printed medication allows for customized medication for individual children as it can be colored and shaped to fit their preferences along with incorporating better tasting and easier-to-chew components (V S et al., 2020). Other uses of 3D printing in the treatment of neonates and pediatric patients are in designing and printing customized user-specific prosthetics that can help increase the efficiency of breath masks used to combat obstructive sleep apnea (OSA) using a continuous positive airway pressure (CPAP) machine. Bioprinting would also allow the fabricating of equivalent tissue to treat burns or surgical scarring that could be more traumatic for children. Finally, 3D-printed organs would help prevent "too-large-for-size" issues when dealing with the need for an organ transplant (V S, 2021).

Otorhinolaryngology

According to Tiwari et al. (2020), 3D-printed models of the ear (otology) and the nose and sinus (rhinology) created using CT scans of patients were useful tools for planning surgeries and training medical students. Additionally, 3D-printed prosthetics were utilized in facial reconstruction to recreate a patient's facial structure more accurately after an accident. Lastly, 3D printed models were used to educate patients on potential surgeries involving their head and neck and with planning and training for the complicated surgeries.

Investigation of different filaments for nasal cartilage implants

A deviated nasal septum can be a constant source of nasal and sinus issues for a patient. The ability to 3D print a nasal septum implant would allow the patient's body to heal and recover while preventing collapse and complications. Gnatowski et al. (2023) determined that the medical filament Bioflex was the ideal material for this application due to its approximation of natural tissue, lack of degradation, and flexibility. However, it was determined that Bioflex alone was not ideal, so it would need to be mixed into another material.

Pediatric Dentistry

3D printing could alter pediatric dentistry drastically as it could alter the learning patterns and educational protocols in the field. Instead of requiring the extraction of teeth for study, enlarged 3D models could be printed. This would enhance the learning and planning of any necessary procedures including tooth extractions, root canals, or braces installation (Shaheen et al., 2022).

Pelvic Fractures

Reconstructing the pelvis due to a fracture is complex and difficult. By utilizing the technology, surgeons were able to get a full understanding of the extent of the fracture and plan how to repair it before beginning the surgery. Using CT scans to construct and print 3D models of patients who had experienced pelvic fractures showed a decrease in operation time and blood loss along with increased pelvic function and higher satisfaction compared to traditional treatment (Wang et al., 2020).

Personal Protective Equipment and Point-of-Care Testing

The ability to detect and diagnose diseases (such as COVID-19) at the point nearest to the patient is crucial to help determine the best course of treatment and to begin the treatment as soon as possible. 3D printing enables the production of rapid detection devices that are easily modified to handle an outbreak of disease while also printing customizable personal protective equipment for healthcare workers (Kalkal et al., 2022).

Prototyping

Rothenberg et al. (2017) were able to construct a prototype for a reciprocating syringe (used in ultrasounds) using a 3D-printed design and off-the-shelf hardware. This allowed for testing of the prototype by technicians and immediate revision of the design without the need to wait for delivery of the new version. This would allow hospitals or medical offices to easily produce and utilize medical devices from downloaded or in-house designs without having to order and store items that may be used rarely.

Methodology

This research project was a systematic review of the existing uses of 3D printing in healthcare to identify the current uses, any current overlap, and any potential cross-utilization of the technology across medical specialties. The research consisted of searching Galileo, the University System of Georgia's online library catalog (*GALILEO Search*, n.d.) for full-text, peer-reviewed, scholarly articles using the terms: "3D printing", "three-dimensional printing", "healthcare" and "health". Articles from 2018 or later were selected for the review. The 25 chosen articles were checked for duplicates or incomplete submissions and those were removed. The articles were read while taking thorough notes to allow for the coding of topics. Articles were codified according to the main medical specialty that was discussed and the main use of 3D printing discussed in the article. Discussion of the current uses of 3D printing in healthcare and the potential cross-utilization will help to further the applications of the technology and expand the potential avenues of research.

Results

The current uses of 3D printing in healthcare are summarized in Table 1, which shows the key findings for 3D printing in healthcare are drug manufacturing, printing a 3D representation of a patient's anatomy, 3D printing prototypes, and customized medical equipment.

Table 1: Current uses of 3D printing in healthcare

Use	Medical Specialties	# of articles
Drug manufacturing	General and Pediatrics	8
3D representation of a patient's anatomy	Cardiology, Orthopedic, and Otorhinolaryngology	7
3D printing a prototype for testing purposes.	Immunology	3
Printing customized medical equipment for implantation	Dental, Neonatal and Otorhinolaryngology	4

In addition, the research articles showed different materials that were tested and determined to have varying results when used to create a 3D-printed implant for medical specialties, these are summarized in Table 2.

Table 2: Materials for 3D printing in healthcare

Material	Use	# of articles
Bioflex	Otorhinolaryngology implants	1
Biominerals	Bone tissue engineering and implants	1
Biopolymers	Surgical mesh	1
Ceramics	Dental and Orthopedic	1
Coffee grounds	Dental and Medication	2
Composites	Orthopedic implants	1

Material	Use	# of articles
Gelatin-carrageenan	Pediatric medications	2
Metal	Orthopedic implants	2
Polymers	Orthopedic implants	2

The key findings that emerged from the literature regarding 3D printing in healthcare is that it is currently viable for select purposes such as printing custom medical implants, 3D representations of a patient's anatomy for surgical planning purposes, rapid prototyping or customization of medical equipment and has the capability to allow for 3D printed medications.

Discussion

3D printing of medication would be beneficial to all areas of healthcare as it would allow the customization of pills for individual patient needs. Medication could be customized by specifying the exact dosage of medications, mixing multiple medications into a single pill, allowing for released timings of medications and even allow for a flavored coating or infusion. This would make pills easier to swallow or chew (particularly for children) and prevent over- or under-dosing a patient. In addition, it would also alleviate the medication storage need for hospitals and the possibility of expired medication being wasted or given to patients by mistake. An area of concern is the regulatory needs for dealing with 3D printed medication (Kumar Gupta et al., 2021).

3D printing has the potential to impact healthcare across various medical specialties with multiple uses. Sonographers, radiologists, and cardiac surgeons are already benefiting from 3D printing patients' blood pool and myocardium for detailed study and surgical practice, as are otorhinolaryngologists with models of patients' ears, nose, and sinus cavity and orthopedists with hip and knee arthroplasty. Wang et al. (2020), showed that patients with pelvic fractures benefited from pre-surgery planning using a 3D printed model by decreasing blood loss and surgery length. These results could be applied to other medical fields to assist in planning complex and lengthy surgeries to help reduce the chance of errors and the amount of time the patient is under anesthesia while also reducing the recovery time for the patient. One field that this application of 3D printing would benefit greatly is neonatal and pediatrics due to the difference in size and complexity encountered when dealing with babies and children.

Several fields already use 3D printing for prototyping and printing custom implantable devices. Expanding the use for these purposes into different fields would enable less expensive and better fitting implants along with the ability to test out products in a timely manner. By 3D printing prototype implants or medical devices, doctors and patients could test fit and try out the devices and make necessary adjustments much more easily and quickly than using a traditional manufacturing technique. This would also enable the sharing of 3D printable designs with other patients and medical professionals across the globe. In addition, according to Javaid et al., 3D printing allows for better integration of the physical supply chain due to the ability to manage the goods from inception to end-of-life (2022).

The results of the research project show that there is considerable potential for cross-utilization between the materials tested. Orthopedists and their patients would benefit greatly from the ability to utilize biominerals in printing replacement bones and joints, while dentists could benefit from the use of coffee grounds in printing dental implants. Utilizing biopolymers and Bioflex allow for better nasal and sinus implants which could also cross over into cardiac and orthopedic surgery.

Conclusion

3D printing offers a wide variety of materials and uses across various medical specialties. The possibilities that exist are staggering as the technology matures and acceptance of it grows. As the usage

of 3D printing increases and the capabilities are refined, there will be a continued need to ensure that it is being used to its full potential by each medical specialty. While the medical specialties that currently utilize 3D printing are currently limited, those could expand to include other areas very easily once the technology matures and is applied to different areas of medicine.

Future research should include the regulatory requirements and restrictions for 3D printing usage in healthcare as the requirements will differ depending on the intended usage. Another area of future research would be the ability to 3D print replacement organs using a patient's DNA and the survival rates of using those versus transplanted organs.

References

Andreadis, I. I., Gioumouxouzis, C. I., Eleftheriadis, G. K., & Fatouros, D. G. (2022). The Advent of a New Era in Digital Healthcare: A Role for 3D Printing Technologies in Drug Manufacturing? *Pharmaceutics*, *14*(3), 609. https://doi.org/10.3390/pharmaceutics14030609

Bruzzone, P. (2008). Religious aspects of organ transplantation. *Transplant Proceedings 2008 May*. PubMed. https://doi.org/https://doi.org/10.1016/j.transproceed.2008.03.049

Domínguez-Robles, J., Martin, N., Fong, M., Stewart, S., Irwin, N., Rial-Hermida, M., Donnelly, R., & Larrañeta, E. (2019). Antioxidant PLA Composites Containing Lignin for 3D Printing Applications: A Potential Material for Healthcare Applications. *Pharmaceutics*, *11*(4), 165. https://doi.org/10.3390/pharmaceutics11040165

GALILEO Search. (n.d.). Retrieved February 27, 2024, from https://www.galileo.usg.edu/

Gang, F., Ye, W., Ma, C., Wang, W., Xiao, Y., Liu, C., & Sun, X. (2022). 3D Printing of PLLA/Biomineral Composite Bone Tissue Engineering Scaffolds. *Materials*, *15*(12), 4280. https://doi.org/10.3390/ma15124280

Gnatowski, P., Gwizdała, K., Kurdyn, A., Skorek, A., Augustin, E., & Kucińska-Lipka, J. (2023). Investigation on Filaments for 3D Printing of Nasal Septum Cartilage Implant. *Materials*, *16*(9), 3534. https://doi.org/10.3390/ma16093534

Goh, O., Goh, W., Lim, S., Hoo, G., Liew, R., & Ng, T. (2022). Preferences of Healthcare Professionals on 3D-Printed Tablets: A Pilot Study. *Pharmaceutics*, *14*(7), 1521. https://doi.org/10.3390/pharmaceutics14071521

Javaid, M., Haleem, A., Singh, R. P., & Suman, R. (2022). 3D printing applications for healthcare research and development. *Global Health Journal*, *6*(4), 217–226. https://doi.org/10.1016/j.glohj.2022.11.001

Kalkal, A., Allawadhi, P., Kumar, P., Sehgal, A., Verma, A., Pawar, K., Pradhan, R., Paital, B., & Packirisamy, G. (2022). Sensing and 3D printing technologies in personalized healthcare for the management of health crises including the COVID-19 outbreak. *Sensors International*, *3*, 100180. https://doi.org/10.1016/j.sintl.2022.100180

Karandikar, M & Rahul, Dr & Tayade, Motilal. (2020). Three-dimensional (3D) Printing applications in Healthcare sector in India. Pravara Medical Review. 12. 40-44. 10.36848/PMR/2020/12125.51225.

Kholgh Eshkalak, S., Rezvani Ghomi, E., Dai, Y., Choudhury, D., & Ramakrishna, S. (2020). The role of three-dimensional printing in healthcare and medicine. *Materials & Design*, *194*, 108940. https://doi.org/10.1016/j.matdes.2020.108940

Kumar Gupta, D., Ali, M. H., Ali, A., Jain, P., Anwer, Md. K., Iqbal, Z., & Mirza, Mohd. A. (2022). 3D printing technology in healthcare: Applications, regulatory understanding, IP repository and clinical trial status. *Journal of Drug Targeting*, *30*(2), 131–150. https://doi.org/10.1080/1061186X.2021.1935973

Liang, E., Wang, Z., Li, X., Wang, S., Han, X., Chen, D., & Zheng, A. (2023). 3D Printing Technology Based on Versatile Gelatin-Carrageenan Gel System for Drug Formulations. *Pharmaceutics*, *15*(4), 1218. https://doi.org/10.3390/pharmaceutics15041218

Liang, J., Zhao, X., Pan, G., Zhang, G., Zhao, D., Xu, J., Li, D., & Lu, B. (2022). Comparison of blood pool and myocardial 3D printing in the diagnosis of types of congenital heart disease. *Scientific Reports*, *12*(1), 7136. https://doi.org/10.1038/s41598-022-11294-6

Reeves, K. (2023). 3D Printing: Bridging the Gap Between Radiologists and Surgeons. *Applied Radiology*, *52*(3), 30–33.

Rothenberg, S., Abdullah, S., & Hirsch, J. (2017). 3D Printing Prototypes for Healthcare Professionals: Creating a Reciprocating Syringe. *Journal of Digital Imaging*, *30*(5), 566–571. https://doi.org/10.1007/s10278-017-9953-x

Shaheen, S. R., Sridevi, E., Sankar, A. S., Krishna, V., Sridhar, M., & Sankar, K. S. (2023). Contemporary era of Three-dimensional printing in pediatric dentistry: An overview. *Journal of Oral Research and Review*, *15*(1).

Tiwari, D., Vobilisetty, R. K., & Heer, B. (2022). Current Application and Future Prospects of 3D Printing in Otorhinolaryngology—A Narrative Review. *Indian Journal of Otolaryngology and Head & Neck Surgery*, *74*(1), 123–126. https://doi.org/10.1007/s12070-021-02634-5

V S, S., Panigrahy, N., & Rath, S. N. (2021). Recent approaches in clinical applications of 3D printing in neonates and pediatrics. *European Journal of Pediatrics*, *180*(2), 323–332. https://doi.org/10.1007/s00431-020-03819-w

Wang, J., Wang, X., Wang, B., Xie, L., Zheng, W., Chen, H., & Cai, L. (2021). Comparison of the feasibility of 3D printing technology in the treatment of pelvic fractures: A systematic review and meta-analysis of randomized controlled trials and prospective comparative studies. *European Journal of Trauma and Emergency Surgery*, *47*(6), 1699–1712. https://doi.org/10.1007/s00068-020-01532-9

Yu, W., Yuan, T., Yao, Y., Deng, Y., & Wang, X. (2023). PLA/Coffee Grounds Composite for 3D Printing and Its Properties. *Forests*, *14*(2), 367. https://doi.org/10.3390/f14020367

Zhang, R., Lin, J., Chen, F., Liu, W., & Chen, M. (2021). Clinical and radiological outcomes in three-dimensional printing assisted revision total hip and knee arthroplasty: A systematic review. *Journal of Orthopaedic Surgery and Research*, *16*(1), 495. https://doi.org/10.1186/s13018-021-02646-5