Creation of a 3D Printed Liver Vasculature Model for Preoperative Planning of Arterial Embolization
(Technical Project)

Chronology and Analysis of the Dissemination of 3D Printed Organ Models Between Physicians and Patients
(STS Project)

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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Introduction

One problem that persists in the medical field is the challenge of developing methods to visualize and study human anatomy and pathophysiology, especially methods that are applicable for both doctors and patients. For centuries, cadavers have been the solution for physicians since these offer a physical and visual experience with real organs. However, the use of cadavers has been fraught with controversy, as they were originally procured through grave robbing and murder (Ghosh, 2015). Though this is no longer the case for medical schools and hospitals today, the cost, low supply, ethical concerns, and degradation of the tissue leave cause for concern and limit the implementation of cadavers in modern medical education (Patra et al., 2023). Additionally, while patients' comprehension of their disease improves with use of visual anatomical models, there are currently no standard teaching models for patient education (Moore et al., 2019).

Though 3D printing was first patented in just 1986 and used for automotive parts, 3D printing has evolved into a $10 billion field that is spread across a variety of industries (Hull, 1986; SmarTech Analysis, 2022). In particular, the medical field has benefitted from the ability to rapidly prototype customizable devices and models, resulting in the development of the medical 3D printing (M3DP) industry. According to Chuck Hall, credited with creating 3D printing, "the medical applications [are most surprising]," but "it became pretty clear that this was going to work." (Glass, 2014). One such application of M3DP is the creation of organ models. Currently, these models are implemented

Figure 1: 3D printed liver model of the vasculature (blue and purple) and metastasized tumors (yellow and green) (Huettl et al., 2021).

on a small scale to teach anatomy, practice surgeries, and communicate with patients about their diagnoses (Ventola, 2014). Aside from printing the user's design, these tools are further customized through the choice of material, color, and degree of detail (Figure 1).

If the reduction of cadaver use continues without the widespread adoption of a sufficient alternative method for hands-on learning, the proficiency of future doctors and the comprehension of patients will be damaged (Ghosh, 2015). Physical anatomy models translate lectured content to real life applications and learning. Additionally, M3DP may not reach large-scale utilization if its capabilities are not realized, causing physicians to turn to less adequate tools. Other current methods like virtual reality simulations and handmade clay models lack tangibility and are labor-intensive, respectively.

To address the need for improved surgical training and teaching models, I will print a 3D liver vasculature model as part of my technical project. UVA surgeons will use this model to practice and teach challenging procedures involving the liver's blood vessels. In my STS project, I will study the chronology of the implementation of 3D printed organ models, focusing on the interaction of this technology between clinicians and patients. Together, I will both indicate how 3D printed organ models hold value in teaching for various stakeholders and develop my own model to meet surgeons' needs, which will further the expansion of M3DP as an educational tool.

Technical Topic

Arterial embolization is a minimally invasive procedure that utilizes the insertion of a catheter into the blood vessels in order to occlude a desired vessel with an embolization agent. The focus of this project is on the use of hepatic arterial embolization to cause selective ischemia in order to starve liver tumors of oxygenated blood, which shrinks tumor size and reduces unpleasant symptoms (Lee et al., 2012). Because this process depends on real-time medical imaging to guide the catheter through small vessels, it is a technically difficult procedure, made more challenging due to the patient-to-patient variability of the tumor vasculature (Bagla & Isaacson, 2016). Thus, there is a great need for realistic physical models of liver vasculature that can be used by clinicians to develop technical skills prior to the real surgery in the patient.

Three-dimensional printed models of human anatomy are one such tool that have been used in teaching anatomy and surgical planning. Modern 3D printers and software allow for the modeling and printing of the human liver vascular anatomy and surrounding tissue from real CT angiography data. However, angiography models of human vasculature typically include only large or medium-sized vessels. The printing of small-scale features is a major area of difficulty within M3DP, which is of utmost importance to the printing of vasculature models. Studies have found that “dimensional errors are most variable when small features are printed,” and that features between 0-10mm had the highest error and variance when compared to the original medical images (Nguyen et al., 2023, p. 6). While the human aorta may be on the order of magnitude of centimeters, the smaller arteries and capillaries are roughly one thousand times smaller.

The goal of the project is to extract the hepatic vascular tree from patient CT data in order to 3D print a detailed, hollow model of the blood vessels accessed during hepatic arterial embolization. First, we will use CT images of a liver that has been injected with a contrasting agent to highlight the vessels. Using Rhino 3D Medical and 3D Slicer software packages, we will isolate the desired vasculature from the 2D images to create a 3D digital model, which we will digitally smooth and repair any deformities within that may result from poor CT image resolution. We will print the resulting 3D digital model with a malleable resin using a stereolithography printer. Then, we will use this model to mimic the flow of blood through the vasculature by attaching it to a pump system. While using the same fluoroscopy imaging as is used in the operating room, we will navigate a catheter through the printed vessels to demonstrate that the model is usable for arterial embolization training.

An overarching goal of this project is to recapitulate the minute vessels at a scale as small as feasible through 3D printing. By focusing on proper dimensioning of the hollow vessels, we will create a more true-to-life surgical training tool than currently exists. Previous 3D printed preoperative tools that were similar, though less detailed, led to decreases in surgery duration and increased surgeon confidence, so we expect similarly positive effects (Nakayama et al., 2017). Additionally, we are improving upon past work done with the UVA Interventional Radiology Department that developed primitive vasculature models, since this tool was not developed using real CT images. Our new model will include more numerous, smaller vessels and will be printed as a single object, making it easily portable and simple to attach to the pump system. Overall, the development of this model is intended to contribute to the expansion of M3DP of organ models being used to adequately train physicians using innovative technologies.

STS Topic

As medical knowledge advances, medical schools and hospitals have both the opportunity and challenge of adapting their curricula and practices to these changes. Indeed, clinicians contend with a difficult reality: the doubling time of medical knowledge has increased from seven years in 1980 to just 73 days in 2020 (Densen, 2011). While cadavers have been the gold standard for studying organ structure and practicing surgical techniques, changes in medical curricula in recent decades have limited their use (Ghosh, 2015). More emphasis has been placed on providing clinical experience and reducing costs, which has decreased the time spent interacting with physical anatomical models within medical curricula, despite research describing how these experiences commit information to memory (Ghosh, 2015; Kappers, 2011; Memon, 2018). However, clinicians are not the only group facing challenges understanding anatomy and surgical procedures: patients awaiting surgery often lack knowledge surrounding their diagnosis and treatment. Typical communication techniques to educate patients include verbal discussion using patients' medical scans, but research shows that adequate understanding of this information only occurs about one-third of the time (Falagas et al., 2009). Preoperative stress occurs in 60-80% of patients before their surgery, with unclarity about their disease and surgery being key stressors (Akutay & Ceyhan, 2023). The hormones produced when patients are stressed are linked to impaired wound healing and higher postoperative pain, so proper understanding is critical to surgical outcome (Stamenkovic et al., 2018). Thus, there is a need among patients and physicians to improve education through innovative tools.

Used as a technique to address these educational deficits, medical 3D printing is one of the most promising modern technologies changing medical practice. The printing of patient-specific organ models from medical scans has opened new opportunities for clinicians and patients. Research comparing cadaveric and 3D printed anatomical heart models found that students significantly benefitted from handling the printed model, while another study found that use of 3D printed models required less time for studying the anatomy and improved understanding compared to 2D medical images (Lim et al., 2016; Marconi et al., 2017). Similarly, comprehension and satisfaction of pediatric cancer patients and their parents was compared between the use of patients' CT images and custom 3D printed organs. Families' knowledge of the procedure, anatomy, and physiology improved significantly after being educated by the physician with the 3D model as opposed to the images. Even more, the families indicated that they felt more involved and reassured with this improved education technique (Yang et al., 2018).

From this research, it can be argued that patients and medical professionals interact with 3D printed organ models in unique ways. Whereas clinicians use these models to visualize anatomy and hone surgical skills, patients view these as a tool of understanding and reassurance. In other words, these groups interact with models differently due to their situational context: being a highly educated professional compared to an ill individual coping with their diagnosis. Accordingly, the STS framework through which I will evaluate my research is the diffusion of innovation (DOI). Through this lens, diffusion can be defined as "the acceptance, over time, of some specific item - an idea or practice, by individuals, groups, or adopting units, linked to specific channels of communication, to a social structure, and to a given system of values, or culture" (Katz et al., 1963, p. 240). The aspects outlined in this definition, particularly the degree and timing of acceptance and the differences in function of a specific technology between different groups, will guide my interpretation of M3DP. Namely, it can be argued that a distinct diffusion of innovation exists for each of these user groups due to their distinct interactions with printed organ models.

Research Question and Methods

This intersection between medicine and 3D printing begs an important question: how has the use of 3D printed organ models disseminated across the medical field over time for teaching of physicians and students in comparison to use as communication tools of anatomy and medical procedures to patients? I will first conduct a literature review to better understand the past and current applications of 3D printing in medicine. Building upon this background, I will focus my search on the emergence of 3D printed organ models, including the years that the models were first developed, the users, and use cases. I will use the PubMed and Compendex databases to conduct my research since these should provide sources at the convergence of medicine and engineering. In doing so, I will develop a further understanding of how clinicians learn and benefit from 3D printed models compared to patients. Overall, I aim to develop a chronology of the use of 3D printed organ models, which can be used to understand what historical or societal factors may have contributed or inhibited their use.

Conclusion

The use of 3D printing for medical applications has already garnered significant interest for its powerful ability to provide visually realistic, tactile models of human anatomy. As indicated through numerous studies, the increased use of M3DP has the ability to benefit both clinicians and patients, though in different ways. By understanding how M3DP has disseminated between clinicians and patients through the lens of the diffusion of innovation, I can identify how to develop and apply 3D printed organ models in order to best serve these two stakeholders. Additionally, development of a CT-based, accurately scaled hepatic vasculature model will improve the teaching and practice of arterial embolization. In the future, this method can be applied to additional interventional radiology procedures. Further research and analysis in this field will allow for increased acceptance of its validity and value, improvement of the technology, and further adaptation of M3DP into standard medical practice.

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