**Beyond the Body: Theorized Implications of Medical 3D Printing on Anatomical Perception**

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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

According to polling in the United States, over a quarter of surgical residents self-admittedly lack confidence in their ability to operate on patients independently (Yeo et al., 2009). Having identified the need for improved methods of teaching and preparing residents, physicians are looking to use 3D printed anatomical models as a supplemental tool to help residents gain the experience necessary to enhance their training. While medical 3D printing is more widely used for the creation of prostheses or implants to save production costs and time, this manufacturing method is now being implemented for the creation of anatomical models with unique and challenging geometries (Ballard et al., 2020; Sun et al., 2023). Using various software programs, physicians and engineers can translate magnetic resonance (MR) and computed tomography (CT) images into patient-specific, one-of-a-kind digital models and print them. The ability to reproduce the structural features of vasculature and other surrounding organs and tissues provides clinicians the opportunity to practice their surgical approach on a tactile model of a specific patient's anatomy before operating. Medical 3D printing is also advantageous for this purpose since the various printing methods allow for the incorporation of materials with different mechanical characteristics and colors, which can better replicate the complex features of the anatomy. However, these anatomical models are currently being implemented in the clinic in a limited capacity and predominantly for inclusion in research publications.

Despite the small-scale implementation, the assessment of the effectiveness of 3D printed anatomical models in the clinic has yielded positive outcomes. The main effects that have been considered are metrics related to anatomical comprehension and performance in the operating room. A review of printed models in the clinic associated their use with a 10-20% decrease in time spent in the operating room (George et al., 2017). To examine surgical strategy in relation to specific patient anatomy, comparison of clinicians' understandings between the use of 2D images, 3D digital models, cadavers, and 3D printed models have been assessed. In these studies, the use of 3D printed models are associated with a reduction in time needed to comprehend the anatomy and improved scores on surgical planning questionnaires (Lim et al., 2016; Marconi et al., 2017). However, among these studies there is a lack of evaluative discussion regarding outcomes of these models outside of performance-based metrics. If these models are being used as tools to teach and practice, it is important to consider potential effects on the viewer at a more theoretical level.

In working on my engineering capstone project, which involves the development of a 3D printed, accurately scaled model of the liver vasculature, I have personally participated in the production of anatomical models used for visualization and surgical preparation aids. Although I exist as an outsider in the typical model production process as an undergraduate with no professional training in medical imaging, the final model is intended to be implemented in the Interventional Radiology Department at UVA Health. Before beginning this project, I had assumed that there must be a highly accurate process that medical professionals use to transform 2D medical images easily and instantaneously into 3D digital models that are suitable for printing. Yet, based on my involvement in developing a model and review of relevant academic and medical case studies, the real process is not quite so simple. As a result, these experiences left me wondering what downstream effects this complex production process may have on the resulting anatomical model and its observer.

I will argue that while 3D printed anatomical visualizations are demonstrative of the movement towards personalized medicine and can provide a useful and tangible experience to the viewer, these models are unable to escape many of the same pitfalls as their 2D predecessors due in part to the subjectivity of their production and limitations of medical technology. First, the literature review will contextualize the use of printed models by providing a timeline and description of past and present medical visualization techniques. Then, I will detail current limitations with medical images and 3D printing and introduce the concept of the disciplining effect of medical visualizations on the human anatomy. In my analysis, I will evaluate secondary sources discussing the development process and perception of 2D medical images in order to compare and contrast to those of 3D printed medical models. By highlighting the similarities and differences in how these visualizations are created, I will be able to initiate the inclusion of 3D printed models into the existing discussion surrounding the limitations of medical visualizations and their potential effects on the perception of human anatomy. Through my analysis, I intend to demonstrate that medical 3D printing processes rely on previously established imaging techniques and user inputs that leave them prone to an erroneous view of anatomy.

## Literature Review

The medical visualization is a foundational tool for the comprehension of anatomy and the diagnosis and treatment of patients which has been made most impactful within the past century due to technological advancement and computerization. Early physicians in the medieval period observed the internal body by dissecting large mammals or more rarely, criminals (Mitchell et al., 2011). These early dissections were done to observe and illustrate anatomy as part of medical education or determine the cause of death. While some historians argue that criminals were dissected because cadaver manipulation was seen as illicit, others suggest that anatomical dissection was on par with funerary practices of the time. They reason that physicians and people understood the value of dissection, and that the public's anti-cadaver sentiment only began later in the 1500s in response to increasingly inhumane procurement and treatment of cadavers and rumors of vivisection (Park, 1994). In either case, physicians were highly interested in gaining insight into the inner workings of the human body and did so through whatever means they deemed necessary. Starting with Vesalius' *De Humani Corporis Fabrica* in 1543 and throughout the following centuries, physicians and anatomists have created anatomical atlases, which are annotated illustrations or graphics of the body (Rosse, 1999). These atlases were the first attempts to include an accompanying anatomical visualization with one's written notes, and they demonstrate the concerted effort to document and share the knowledge of the body.

The pivotal moment in medical visualization that began the digitization of the body was the discovery of X-ray imaging in 1895 (Bercovich & Javitt, 2018). For the first time, physicians were able to observe the internal anatomy of a living person non-invasively. This was followed by the development of CT, MR, and ultrasound imaging in the mid-1900s, which were based off X-ray and comprise the core imaging modalities used today. These 2D imaging methods pose various advantages depending on the tissue type being visualized (Bercovich & Javitt, 2018). While these techniques and medical machinery were improved in the subsequent decades following their initial creation, the medical imaging field remained relatively stagnant. The next innovative change began in the early 2000s and late 2010s, respectively, as 3D printing and virtual reality (VR) simulations have been developed from previous 2D modalities (Lan et al., 2023; Whitaker, 2014). While 2D visualizations currently remain the mainstay, as hospital infrastructure and processes are heavily centered around these methods, the use of 3D visualizations is on the rise in the clinic and in medical schools. Both 3D printing and VR are currently used for anatomical education and preoperative planning, as some physicians have sought to move away from using cadavers in medical schools due to their limited availability and ethical concerns (Ghosh, 2015). Thus, this enduring challenge of determining how to accurately see into the body to gain medical knowledge has persisted for physicians throughout history.

While modern medical visualization techniques have certainly improved upon earlier approaches, limitations persist in both traditional and new visualization methods. There are a wide variety of sources for artifacts in medical images, including movement of the patient, differences in the properties of adjacent tissues, and parameters set on the imaging machine. These errors can lead to challenges in the interpretation of the acquired medical images, which can then result in misdiagnosis of the patient (Budrys et al., 2018; Zhang et al., 2023). As for 3D printed visualizations, small-scale 3D printing remains a challenge but is necessary for recreating detailed anatomical features. For example, many of the models have been developed to practice surgeries that require precise manipulation of the vasculature, so the desired anatomy to be printed in these cases is small, hollow, and tortuous (Hoang et al., 2016; Ventola, 2014). Through analysis of patient-specific printed models, features printed between 0-10mm in size were found to have the highest error and variance when compared to the original medical image data from which they were developed (Nguyen et al., 2023). Other dimensional issues have been found to arise through various aspects of the printing process. Two of the most common printing methods, fused deposition modeling (FDM) and stereolithography (SLA), both face the issue of part shrinkage as the printed material cools or polymerizes, respectively (George et al., 2017). Problems also extend beyond the actual printing; the postprocessing steps used to clean and finalize hollow vasculature models were found to unintentionally increase the inner diameter of printed vessels by eroding away the inner layer of printed material (George et al., 2017). Thus, there are a staggering number of variables and considerations that contribute to the challenge of creating an accurate representation of the human anatomy.

Following the development of advanced imaging technologies, many scholars within the study of medical imaging have put forth the idea that visualizations that are created can be viewed as a way to discipline the human body. In this context, disciplining refers to efforts to standardize, enforce a degree of order to, or lessen nuance within the human anatomy. The creation of the Virtual Human Project (VHP) is a prime example cited amongst these researchers. Created by the National Library of Medicine, the VHP consists of a highly detailed CT scan of one man and one woman, which were intended to be used as a standard reference for anatomy, diagnosis, and the development and testing of computational algorithms (Ackerman, 1998). However, some researchers argue that these standardizing efforts are misguided, as they ignore important anatomical differences between individuals, ethnicities, and ages, among other factors (Prasad, 2005). More generally, others argue that any output of medical imaging is inherently disciplined. Lynch indicates that the scientific images and visualizations that are developed by researchers are what compose the material form of the scientific concept they are intending to capture (1985). When these visualization objects or scientific phenomena reach the point where they become knowable and observable, they have already been disciplined. While the relevance of disciplining has been acknowledged for 2D medical imaging, this discussion has yet to be expanded to explicitly include 3D printed medical visualizations, leaving a key area of the conversation untouched.

I will be using Donna Haraway's take on Cyborg Theory as my guiding theoretical framework. In *Simians, Cyborgs, and Women*, Haraway argues that humans and technology have become so intertwined that humans can be considered cyborgs, or "a hybrid of machine and organism" (1991, p. 149). She finds fault with the all-seeing, all-knowing perspective created by modern technology that has become integrated and normalized into daily life. Referring to this vision as a “god-trick,” Haraway explains that despite their purported objectivity, these perspectives are actually highly dependent on the situated circumstance and the viewer (1991, p. 189). I will apply Haraway’s writing on Cyborg Theory to examine the ways in which medical visualization techniques, namely the 3D printing of anatomical models, may lead to an altered or skewed comprehension of the body. Through this lens, I will also examine how modern medical technologies may lead to a false perception of scientific objectivity and perfection.

## **Methods**

To conduct this research and analysis, I gathered secondary sources that analyze the development process and effect of 2D medical images on the perception of anatomy. Since most current literature on medical visualization revolves around 2D imaging as opposed to 3D representations, I also applied the experiences and understanding gained from my technical capstone project in order to extrapolate upon the existing writing in this field to include realistic 3D printed models in its discussion. Through the course of my capstone project, I have had the opportunity to shadow and speak with interventional radiologists at UVA Health and utilize 3D modeling and printing software to develop a 3D vessel model. Thus, I have gained personal experience with the subjectivity of the manual steps of 2D image segmentation and editing that are necessary to create printed anatomical models. So, my experiences, in conjunction with my STS framework and literature regarding the production of 3D printed anatomical models, will serve as the basis for my interpretation and analysis. In order to base my research in Cyborg Theory discussion, I began my literature search with sources that cited Haraway’s *Simians, Cyborgs, and Women* and then continued to follow related sources.

## Analysis

While not often acknowledged in their general conceptualization, one risk shared among both 2D and 3D medical visualizations is their mischaracterization as depictions of anatomical truth. Rather, these visualizations can more accurately be described as "once or even twice removed from reality" (Kassirer, 1992, p. 829). Technically speaking, the MRI and CT acquisition data is highly processed to create 2D and 3D visualizations, meaning that the data are transformed into a new and separate medical object. For example, the process of acquiring an MR image involves the adjustment of several parameters on the imaging machinery, including repetition time, recovery time, and slice thickness. The alteration of any one of these parameters will affect the resulting data. This mathematical data is then translated using a mathematical model to create an array of pixels that allow the data to be visualized as an image (Katti et al., 2011). The subsequent process of creating the 3D printed anatomical model is quite intensive. The first step requires segmentation of the desired anatomical feature from the rest of the image and conversion of the data into a file type that can be recognized by 3D printing programs. This process can "inadvertently change the appearance of the model" by "removing fine structures from the original model and over smoothing and wrapping surfaces so they no longer reflect the source data" (Leng et al., 2017, p. 4). Because the 3D printed models are developed from 2D images, the errors and inaccuracies of the images are therefore compounded and further incorporated into the printed models. In other words, the 2D images are less accurate than the body, and the 3D models are less accurate than the 2D images. Since there are several detailed steps required to produce a 3D printed model, there are numerous chances where error can and invariably is introduced into the production process. Thus, the visualization begins to take on an identity of its own when created through this process.

Another similar factor that contributes to the incomplete understanding of anatomy through 3D printed models revolves around what becomes hidden during the production process. The accuracy of a 3D model is dependent upon the machinery and programs used to create it. However, artifacts of varying degrees are essentially inevitable in medical visualization, whether 2D or 3D, as a result of these technologies. While the various imaging and processing software programs being employed are robust and can ease many aspects of the modeling process, they are imperfect. The consequence of this is that the features of the data that are not well represented or rendered are deemed unimportant or entirely removed from the model (Burri & Dumit, 2008). Thus, these programs inherently alter the anatomy being produced. When limitations in imaging technology lead to the omittance of certain features, the models stray further from reality. Taking Haraway's perspective on this issue, the model production technology participates in the "semiosis and production in what we call scientific knowledge," where this scientific knowledge is the 3D representation of the anatomy (1991, p. 195). Thus, the limitations of the machinery used to make these visualizations actively affects and creates the scientific knowledge that allows the model's user to perceive the anatomy. Aside from literal features of the anatomy being hidden from the viewer's vision, the full effect of the technology in the production process is also concealed. In a discussion surrounding the creation of medical visualizations, Fitsch stated that "visualizing the statistical data through … images means making the production process, the technical apparatuses and the theoretical assumptions become invisible" (2012, p. 276). Since the final printed visualization that is produced is able to exist standalone from its production process, the error-inducing steps are hidden and allow these visualizations to be perceived as one-to-one depictions of reality. In this view, the technology itself plays a role in defining what anatomical features have significance and what is worthy of being perceived.

Aside from limitations in the visualization production technology, another contributor to the potential overconfidence in anatomical models by the scientific community considering their implementation in the clinic is due to the role of the producers of the visualizations: trained clinicians and technicians. Medical visualization data transfers hands several times throughout the production process, being interpreted and reinterpreted by each person along the way (Figure 1). In comparison to 2D images, additional stakeholders become involved in the production process for 3D printed models. Engineers with expertise in computer aided design (CAD) and 3D printing assist with the creation of the digital model, printing, and post-processing steps (Valls-Esteve et al., 2023). As each actor becomes incorporated into the production process, the individual decisions and analyses that they make become hidden, but these choices are pivotal to the final result of the model. In this production process, the physicians and engineers take on an esteemed role that may contribute to the false understanding of objectivity of the visualization, as Haraway states that "an optics is a politics of positioning" (1991, p. 193). Since these actors possess the anatomical and technical knowledge, and each individual actor is the only person privy to the subjective choices they make, they are positioned as the only ones with the ability to produce this vision. According to Haraway, "the only position from which objectivity could not possibly be practised and honoured is the standpoint of the master… whose Eye produces, appropriates, and orders all difference" (1991, p. 193). Thus, it is these privileged creators, as opposed to the inherent anatomy or wider scientific community, involved in the production process that have the final say about how the process will be carried out, what makes a "good" visualization, and what anatomical features are worth including.

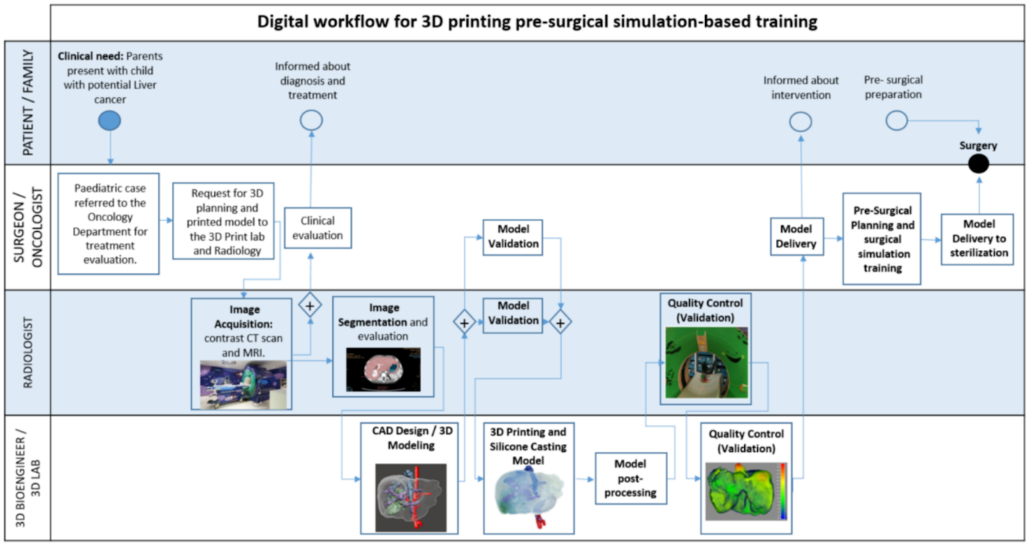


Figure 1: Organization of the various steps and producers involved in the development of 3D printed anatomical models (Valls-Esteve et al., 2023).

Regarding the involvement of physicians in the production and perception of 3D printed models, some may push back and argue that the experts involved in the production know that these models are not entirely accurate depictions of the human anatomy. They may reason that the models are simply understood to be just one part in a collection of tools for diagnosis or treatment planning. However, the particular language used by clinicians around these medical visualizations suggests otherwise. Physicians have described them as a way to “reveal” and “unveil” details of the patient that allow the physician to diagnose and treat (Joyce, 2005, p. 443). Clinicians’ word choice also contributes to the conflation of the medical visualization as equivalent to the body. In ethnographic work conducted by Joyce, one physician stated that “MRI is really the same as the anatomy labs. You can look at the anatomy perfectly, see everything” (2005, p. 444). I would reason that the 3D, physical characteristic of a printed model would make physicians even more likely to conflate the visualization with the real human anatomy. When presented with a physical object that resembles what is seen when opening and operating on a patient, as opposed to a more abstracted 2D medical image, there may be a greater tendency to take the model at face value as an absolute depiction of anatomy. From this perspective, the physicians and engineers themselves do not have an objective view, which results in the visualization that they produce also being a subjective piece of scientific knowledge.

Although the personalized nature of 3D printed anatomical models may avoid the disciplining of the body that results from the creation of universalized models like the VHP, other forms of discipline are still imbedded within patient-specific models. Medical 3D printing has been heralded as a way to assess and treat patients on a case-by-case basis and accept nuance within the anatomy (Itagaki, 2015). However, the disciplining force associated with medical visualizations is not limited to just the effect of the printed visual on the original anatomy, but also the effect of the producer on the visualization. In other words, there is disciplining built into the production process, as the physicians and engineers themselves are disciplined through their education and training and then impose that discipline onto the models they create (Burri & Dumit, 2008). Prasad states that "radiologists are not interested in deciphering the anatomic details of the body"; rather, they focus on the particular aspect or anatomical feature of the anatomy that they are interested in printing (2005, p. 292). They come to see the anatomy not as a coordinated system, but as a "set of notations" or a discrete part to be extracted, observed, and treated (Prasad, 2005, p. 305). Moreover, clinicians come to internalize or expect certain trends in the medical visual based on a given patient demographic, tuning their knowledge to create the visualization through this lens (Prasad, 2005). According to Haraway, "the 'eyes' made available in modern technological sciences shatter any idea of passive vision" and these eyes, which she defines to include synthetic devices and real human eyes, become "active perceptual systems, building in translations and specific ways of seeing" (1991, p. 190). In this view, the perceptual system being put in place can be seen as twofold. Interpreting the model designers as the human eyes and the 3D printed models as a form of "prosthetic eyes," the designer first imparts their own unique interpretation of the anatomy based on their own education, skill, and experiences. Secondly, the resulting model itself becomes a particular way of portraying and seeing the body that is not entirely true to life. The result of this perceptual system's disciplining is that both the model's producer and the general viewer can lose sight of the interconnectedness of the body systems that are being portrayed due to the hyper-focused nature of a model's production and the underlying assumptions being incorporated by the designer.

## Conclusion

By understanding how 3D printed anatomical models make the internal, unseen structures of the body visible through a largely hidden process, one can become aware of their potential to influence the perception of anatomy and the decisions that physicians may make as part of a patient's treatment plan. This interrogation of the production process through Haraway's lens allows one to consider the consequences of each step rather than take the resulting model for granted. I hope that the thoughts and reasoning outlined in my research could serve as a launching pad for future critical assessment of 3D printed anatomical models in the medical space. I believe that further discussion would benefit from ethnographic studies or interviews with the producers of printed models as it would make their inner thoughts and perspectives known, leading to a more multifaceted discourse. I hope that the medical professionals and engineers involved in the model production processes may view my evaluation as a demonstration of the need to improve clarity regarding the limitations that they face throughout their production of scientific knowledge. As Haraway argues, only by acknowledging that one has a partial perspective and partial knowledge can an objective view begin to be reached (1991). Additionally, my research should also encourage innovation and the search for improved methods of medical imaging to address the current state of technology that relies on significant manual adjustments.

Though my findings would caution against the view of 3D printed anatomical models as the pinnacle of medical visualization and surgical practice techniques, it is clear from medical case studies that they do provide additional value to the physician and patient experience. As medical imaging and 3D printing technologies continue to improve, the resulting 3D anatomical models being produced will also benefit from these changes and result in models that are more accurate and realistic. If clinicians and academics are able to conceptualize and communicate about these models in a way that makes clear their position as a manmade apparatus rather than a perfect replica, then these 3D printed tools could help residents to critically assess and respond to novel challenges in the clinic by providing them with a more robust learning experience.

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