At CBMTI, physicians perform neurosurgery procedures on multi-material 3D prints using actual surgical implements

Enhancing Clinical Preparedness

REVIEW OF PUBLISHED LITERATURE ON 3D PRINTING APPLICATIONS FOR MEDICAL EDUCATION AND TRAINING

By Michael Gaisford, Todd Grimm and R. Scott Rader, PhD

While there has been substantial reporting on the use of 3D printing for pre-operative planning, the publications of investigative work, trials and studies related to education of students, residents and practitioners have received less visibility. At the same time, the challenges of educating and training health care professionals on new techniques and procedures are heightened by the limitations of current training modalities. Training organizations often struggle to access a sufficient volume of clinically relevant, realistic training situations for their students. 3D printed static biomodels and physical simulators may be a valuable tool, but the benefits must be better understood.

ABSTRACT

Background

While there has been substantial reporting on the use of 3D printing for pre-operative planning, the publications of investigative works, trials and studies related to education of students, residents and practitioners have received less visibility. At the same time, the challenges of educating and training health care professionals on new techniques and procedures are heightened by the limitations of current training modalities. The challenges and limitations may cause training organizations difficulties in accessing a sufficient volume of clinically relevant, realistic training situations for their students.3D printed static biomodels, which are used to communicate anatomical structures, and physical simulators, which are used to practice medical procedures, may be valuable tools to address the training difficulties, but the benefits must be better understood.

Methods

This research is to evaluate the current state of the published science on the use of 3D printing as a tool for the advancement, acceleration and improvement of medical training. Stratasys worked with an independent third party to conduct a search of recent medical literature citing the use of 3D printing. The resulting scientific papers were then filtered to yield only those related to education and training. The approaches, results and findings were then summarized.

Results

The authors summarize 31 scientific papers in which anatomical replicas created via 3D printing were used as adjuncts or alternatives to traditional medical education tools. These tools were used across nine specialties and in general medical training.

Conclusion

Static biomodels and physical simulators constructed from 3D printing are widely applicable and generally accepted as satisfactory or superior alternatives to traditional education tools that address the limitations of conventional training aids. As such, 3D printing can be employed to expand access to hands-on learning, while minimizing the risks associated with training in the operating theater, and improve skill levels for complex procedures.

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TRADITIONAL TRAINING METHODOLOGIES AND LIMITATIONS

Traditional training tools include plastinated models; virtual reality models; commercial, mass-produced models; cadaveric dissections and prosections; virtual reality simulators; and practical, in vivo surgical participation. The cited limitations of each, which are the motivations to use 3D printing, are listed below.

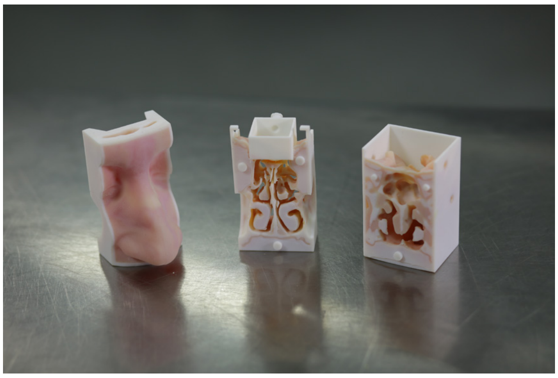

Figure 1: Ear nose throat surgery model in a multi-material jetting 3D printer. Able to achieve resolutions of less than 30 microns, material jetting can replicate fine structures.

Biomodels

- Plastinated cadaveric models
  - See "Human cadaveric dissection" below
  - Distortion of structures and tissues
  - Expense
  - Rigidity, lacking tactile realism
  - Often, lack of pathology
  - Health and safety concerns (for in-house plastination labs)
- Virtual reality models
  - Lacking tactile, haptic feedback
  - Cognitively, perceptually demanding
  - Little variation in anatomy
- Commercial, mass-produced models
  - Rudimentary and not suited for advanced procedures
  - Hypothetical or caricaturized anatomy
  - Limited to a few anatomical variations
  - Lacking pathology
  - Expensive and single use

Simulators

- Human cadaveric dissection and prosection
  - Scarcity of specimens
  - Limited variations (e.g., infant)
  - Limited access, such as due to controversy or religious beliefs
  - Expense
  - Health and safety concerns
  - Distorted, collapsed or otherwise altered structures
  - Often, lacking pathology
- Virtual reality simulators

    - Expensive
    - Not portable
    - Overly coarse anatomy
    - Unrealistic haptic feedback

Practical Experience (In Vivo Training)

- Limited availability due to:
    - Logistics
    - Patient risk (complications)
    - Work-hour restrictions
    - Efficiency pressures (to minimize procedure time)
- Scarcity of uncommon procedures
- Step-wise training (master one step per session)
- Number of sessions required (for complex procedures)

Alternative medical training tools are needed as adjuncts to those currently used. The primary drivers to develop new sources of training are limitations in traditional training methods, complexity of procedures, the rise of new procedures, and variance in human anatomy due to age and pathologies.

These challenges are amplified by the change in the work environment that is further complicated by the expansion of medical knowledge, which pressures trainees to learn more in less time. Opportunities for developing and assessing skills in students and residents in a safe environment are becoming rare due to a variety of factors such as work-hour reductions, financial pressures and risk minimization for patients. An additional noted challenge is the scarcity of educational tools or specimens suitable for uncommon procedures, diseases and pathologies.

Although the focus of the papers is on medical students and residents, it is often experienced practitioners who are in need of alternative training tools. These tools could be used when practicing a new or advanced procedure — rather than relying on previous experience and applying it, for the first time, on a real patient — to refresh skill sets for rare procedures, or to practice on patient-specific anatomy.

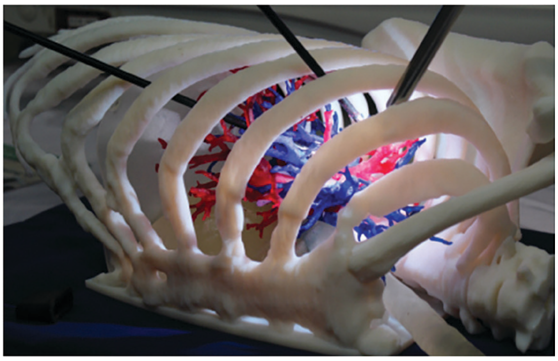

Figure 2: At Kobe University, 3D printed models allow surgeons to practice procedures before performing them on human patients.

All of the reviewed papers evaluated the use of 3D printed anatomical models as alternative training tools for clinical education and simulation. Based on the ability to simulate virtually any geometry, and in some cases varying tissue and anatomy characteristics, the researchers hypothesized that these anatomical replicas would present a new modality for clinical training.

3D PRINTING STUDIES AND TRIALS

Stratasys worked with an independent third party to conduct a search of recent medical literature citing the use of 3D printing. The resulting scientific papers were then filtered to yield only those related to education and training. In these, 3D printing is the vehicle for production of anatomical replicas for two intents. One: study and visualization (static biomodels) and, two: simulation of medical procedures (physical simulators).

The search identified 31 scientific papers in which anatomical models created via 3D printing were used as adjuncts or alternatives to traditional medical education tools. Twenty-seven of the papers present discoveries on the use of 3D printing to create static biomodels and physical simulators. The balance (Rehder et al[1], Drake et al[2], Chandrasekhara[3] and Balestrini et al[4]) offer commentary on others' 3D printing research or their own opinions on current and future educational tools.

The papers presented a range of experiences including a mix of small-scale studies (prospective or pilot) and third-party assessment of demonstrators that employ 3D printing. Seven of the papers investigate the efficacy of 3D printed static biomodels and 20 do the same for physical simulators that use 3D printed simulants (Table 1). Nearly all of the results are qualitative.

For static biomodels, 3D printed training tools are compared to 2D radiographic imaging (computed tomography [CT]), 3D digital models, plastinated models and cadaveric specimens. For physical simulators, the comparisons are drawn against cadaveric dissection, virtual reality simulators and in vivo training during surgical procedures.

Nineteen of the scientific papers had a study population of less than 10 participants. The largest study had 120 participants[8]. Considering the small populations in the studies, all of the papers note or imply that the positive results for 3D printing would need large-scale studies to obtain definitive results. However, each stated that the research demonstrated the value and viability of 3D printing

Therapeutic Areas by Replica Type

STATIC BIOMODELS FOR ANATOMIC VISUALIZATION AND EVALUATION	PHYSICAL SIMULATORS FOR DIAGNOSTIC AND PROCEDURAL SKILLS DEVELOPMENT
• Oncology - Kidney (renal tumor)[5] - Pancreatoduodenectomy (radical nephrectomy)[6] • Ophthalmology - Orbit[7] - Orthopedics - Spine (fracture)[8] - Neurology - Lumbar (posterior)[9] • General – multiple disciplines - Portal and hepatic venous anatomy[10] - Anatomy (general)[11]	• Anesthesiology - Bronchoscopic imaging[12] • Cardiology - Ventricular septal defect imaging and repair[13] • Gastroenterology - Ampullectomy[14] - Endoscopic ultrasonography[3] • Ophthalmology - Orbital decompression[15] • Otology - Temporal bone drilling/dissection[16-19] • Otorhinolaryngology - Endoscopic base-of-skull surgery[20] • Neurosurgery - Spinal instrumentation, percutaneous stereotactic lesion procedure, and ventriculostomy[21] - Brain retraction[22] - Ventriculostomy (external ventricular drain placement)[23,24] - Endoscopic endonasal drilling[25] - Cerebrovascular intervention (aneurysm)[26] - Craniotomy and tumor excision[27] - Thalamic lesion biopsy[28] - Intraventricular endoscopy (hydrocephalus)[29] • Urology - Fluoroscopy-guided percutaneous nephrolithotomy[30] - Pediatric pyeloplasty (laparoscopic)[31]

Table 1: Summary of therapeutic areas, anatomy and procedures covered by the reviewed papers.

as an adjunct or alternative to traditional training methods.

METHODOLOGIES

Workflow

The studies used a common workflow for both static biomodels and physical simulators. The processes began with CT or magnetic resonance imaging (MRI) data, from patients or cadavers, that generated Digital Imaging and Communications in Medicine (DICOM) files*. These were then imported into software programs where the anatomy was segmented to create the desired anatomic structures. Where needed, this data was further modified and repaired. Next, polygonal mesh (STL) files were generated for 3D printing (Figure 3).

Following 3D printing, the anatomical replicas were used as-is, coated, painted or dyed. For the physical simulators, some studies used 3D printed replicas combined with other materials to imitate tissue, such as dura and skin.

*In one study (Adams et al[7]), laser scanning captured geometry, texture and color of prosected, plastinated models.

Typical Workflow for 3D Model Development

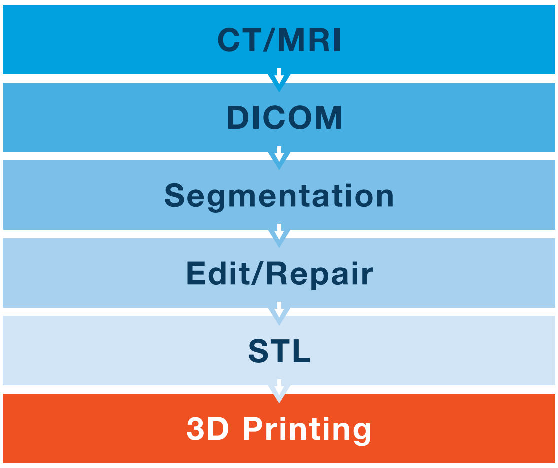

Figure 3: Generating a 3D model of patient-specific image data.

3D Printing's Role

Predominantly, 3D printers directly fabricated the biomodel or physical simulator. However, six studies used 3D printing to create molds that were then used to cast anatomic structures in materials that better simulate human tissue (Mashiko et al[22], Ryan et al[23], Tai et al[24], Tai et al[25], Wurm et al[26], Cheung et al[31]). The cast materials included silicone, polyurethane, hydrogel, gelatin/agar mixture and high-acyl gum. In most of these cases, the molded items were combined with 3D printed anatomic replicas.

One study (Holt et al[14]) used 3D printing to fabricate mechanical objects to attach and hold an animal organ and commercially purchased, plastic duodenum.

3D Printing Technologies

Three 3D printing technology classes dominate in the biomodel and simulator applications. The number of studies that used material jetting, binder jetting and material extrusion where nine, 12 and eight, respectively. There were four instances of vat photopolymerization and one of powder bed fusion. For descriptions of these 3D printing technology classes, see Table 2.

The authors do not provide details regarding the factors in technology selection. However, it may be inferred that the key criteria were material properties (especially when simulating human tissue and organs), cost and color. Another inference is that convenience played a role — using technologies readily available at one's facilities.

In the static biomodel applications, binder jetting was used predominately for its combination of multi-color printing and low-cost, plaster-like materials. Material extrusion and powder bed fusion were most likely selected for the strength of the models, made from thermoplastics, when a single color was acceptable.

Physical simulations based on material jetting often employed the technology's ability to create multi-material and multi-color, which allows a single piece to have a variety of mechanical

Summary of 3D Printing Technology Classes

CLASS	PROCESS	EXAMPLE
Binder jetting	Liquid bonding agent is selectively deposited to join powder materials.	ColorJet printing
Directed energy deposition	Focused thermal energy fuses materials by melting as they are being deposited.	Laser engineered net shaping
Material extrusion	Material is selectively dispensed through a nozzle or orifice.	Fused deposition modeling (FDM®)
Material jetting	Droplets of build material are selectively deposited.	PolyJet™
Powder bed fusion	Thermal energy selectively fuses regions of a powder bed.	Laser sintering
Sheet lamination	Sheets of material are bonded to form an object.	Selective deposition lamination
Vat photopolymerization	Liquid photopolymer in a vat is selectively cured by light-activated polymerization.	Stereolithography

Table 2: Primary source: ASTM Int'l.

properties and visual characteristics. For example, in the brain tumor study (Waran et al[27]), the replica was printed with mechanical and visual properties that mimicked skin, bone, dura and tumor tissue. Binder jetting was used most often to mimic bone. With the proper infiltrants and coatings, the studies found that there was acceptable to good tactile realism when performing a procedure. Material extrusion was primarily used for static anatomic features, such as a skull frame, that would not be manipulated during a procedure.

Table 3 lists the number of 3D printed anatomic structures by technology class and application.

3D Printed Anatomical Structures by Technology Class and Application

	BIOMODELS	SIMULATORS	MOLDS/FIXTURES	TOTAL
Binder Jetting	3	8	1	12
Material Extrusion	2	5	2	9
Material Jetting	0	8	1	9
Powder Bed Fusion	2	0	0	2
Vat Photopolymerization	1	2	0	3

Table 3: Number of 3D printed anatomic structures by technology class and application presented in reviewed literature.

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In this table, the anatomic structure count reflects unique structures printed as one piece. For example, the replica for the brain tumor study (Waran et al[27]) represents one anatomic structure even though the 3D print included the skull, brain, dura, skin and tumor. Meanwhile, the ventriculostomy procedure in Tai et al[24] represents four anatomic structures (skull, brain, insert and face) because each was 3D printed separately. Therefore, the anatomic structure count for material jetting is somewhat misleading because it is the only multi-material-capable technology discussed in the reviewed literature.

Table 4 illustrates the use of 3D printing technology on a paper-by-paper basis. These results reflect the technologies used in each study and are independent of both the number of anatomical structures and quantity of models printed.

3D Printing Technology by Paper	
	SCIENTIFIC PAPERS
Binder Jetting	11
Material Extrusion	8
Material Jetting	8
Powder Bed Fusion	1
Vat Photopolymerization	3

Table 4

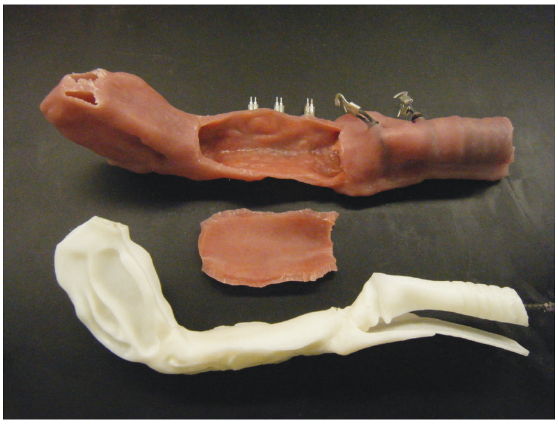

Figure 4: The University of Minnesota developed an airway intubation trainer built using 3D printed components.

Simulators

When fabricating a physical simulant of human anatomy with 3D printing, the replicas were paired with the actual surgical tools that would be used during a procedure. Tools cited in the studies include items such as image guidance stations, endoscopes, fluoroscopes, bronchoscopes, drills and operating equipment. For additional realism, some of the studies also included surgical drapes and other ancillary surgical supplies.

In one study (Bova et al[21]), 3D printing was a component of a "mixed reality" simulator that combined physical and virtual elements. The author's goal was to provide a rich, complete simulation to fully mimic the real world.

Four of the studies (Mashiko et al[22], Ryan et al[23], Tai et al[24], and Waran et al[29]) extended the physical simulation beyond what is possible with cadaveric dissection and virtual simulation by adding fluids to the system. For example, the ventriculostomy procedure in Tai et al[24] used a water reservoir connected to the ventricle to further the realism of the procedure.

Beyond the scope of the papers reviewed, there is evidence, from first-hand accounts**, that there is keen interest in introducing fluids and gases into the simulators to replicate the experience of a surgical procedure on a live patient. Models are also incorporating advanced sensors to provide monitoring and feedback of the trainee's performance while using the simulator. These enhancements can be relatively easy to incorporate into the 3D printed replica through simple changes to the digital model that allow access and connectivity to additional systems.

RESULTS AND FINDINGS

The studies unanimously conclude that 3D printing is a viable and effective alternative for education and training of medical students, residents, fellows and practicing doctors. In nearly every measure and domain, 3D printed biomodels and simulator replicas are found to be comparable or superior to 2D imaging, 3D recreations, plastinated models, standardized synthetic (plastic) models and virtual simulators.

The studies also find that 3D printed replicas are an adjunct to cadaveric dissection, the "gold standard,"[18] and on-the-job in vivo training. While practicing on real human structures is preferred, 3D printing has its advantages. It addresses many of the limitations related to cost, availability, risk, safety and pathology that were previously described. Additionally, when compared to cadaveric dissection, depending on technology selection, 3D printing can offer the added value of mimicking the properties of living tissue that is altered in cadaveric specimens, for example, loss of pliability due to desiccation[18].

3D printing does, however, have its limitations. Those cited by the scientific papers are documented in the section "Limitations and Considerations."

Time and Cost

All studies report 3D printing to be a cost-effective solution. Based on the expense of the 3D printed replicas, excluding capital outlay and ongoing operational costs, the studies state that the technology is more affordable than all other physical models.

Adams et al[7] (Figure 5) report a 90% to 95% cost reduction versus plastinated models, and McMenamin et al[11] show that a $14,000 plastinated model can be replaced by a $350 3D printed

*** Exposure to unpublished work by Stratasys customers.*

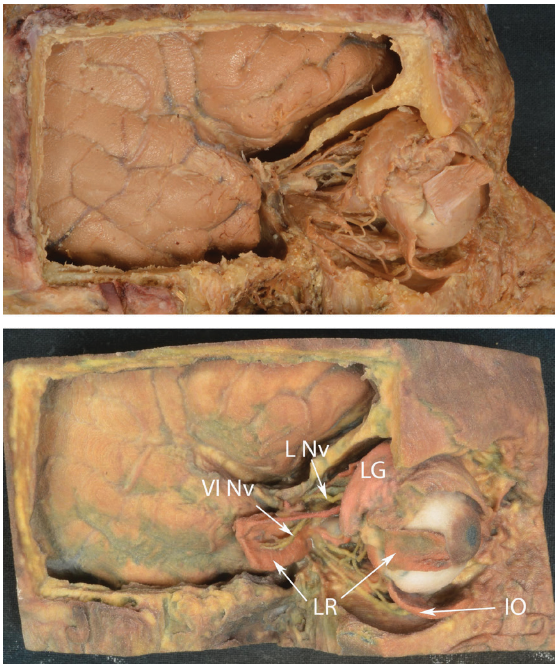

Figure 5: From Adams et al, cadaver dissection (top) and 3D print (bottom) of the orbit from the lateral perspective. Key anatomical landmarks include the lateral rectus (LR), inferior oblique (IO) muscle, abducens nerve (VI Nv), lacrimal gland (LG), and the lacrimal artery and lacrimal nerve (LNv).

replica. The studies report 3D printing costs, based on material consumption, ranging from $10 to $2,600.

Compared to virtual reality simulators, the studies also state that 3D printing is cost effective. However, they note that it is difficult to perform a direct comparison since the virtual solutions are capital intensive but have little or no operational cost.

The studies report, in some cases, the time to produce 3D printed replicas. However, there are no direct comparisons to alternative training tools. The time to create the models ranges from one hour to four days, which in some cases included the time to produce molds and cast anatomic structures.

Training Outcome

One study (Li et al[8]) compares the impact and effectiveness of 3D printing as an educational tool with that of other methods. In it, study participants diagnosed spinal fractures using three visualization tools: CT, virtual models and 3D printed biomodels. The results show those who used 3D printing completed the diagnosis and evaluation faster and with more correct answers. The participants also had more confidence in their results. See Table 5 for results.

The authors conclude that 3D printed replicas improved learning efficiency, helped to acquire expertise and increased interest and enthusiasm.

Realism

To be a viable educational and training tool, 3D printed replicas must accurately and realistically present anatomic structures. All of the studies conclude that 3D printing satisfies these criteria.

Anatomy: Balestrini et al[4] report that the 3D printed models were accurate to within 0.2 mm

Study Participant Performance by Training Method

METHOD	TIME TO COMPLETE (MINUTES)	CORRECT ANSWERS	CONFIDENCE (%)
3D Printing	6.3	7.2	75
Virtual Model	6.3	6.4	62.5
CT	13.5	4.1	25

Table 5: Mean values for 40-participant groups. Source: Li et al.[8]

(0.007 in.) and that they represented real human anatomy as opposed to the idealized versions in commercially available, synthetic models. Adams et al[7] concur and report that they were highly realistic; all anatomic structures were adequately reproduced; and small structures like nerves and arteries were readily distinguishable.

Versus mass-produced, synthetic models, McMenamin et al[11] note that 3D printed replicas have the advantage of realism. In this study, the authors state that the synthetic models are "copies or molds of 'hypothetical' or 'caricatured' anatomical specimens that often lack important, specific details."

When compared to cadaveric anatomy, Hochman et al[16] find 3D printing to offer a better representation than virtual simulators in 14 of 17 categories. On a 7-point scale, 3D printing had an average value of 5.5.

McMenamin et al[11] note an additional advantage: 3D printing accurately reproduced negative spaces such as sinuses and coronary vessels. This report, like that of Adams et al[7], also states that 3D printing produces highly realistic replicas where small nerves and vessels can be distinguished.

Haptic feedback: Narayaman et al[20] reveal a consensus that 3D printing yielded a simulation that was realistic and useful in learning complex procedures. Participants in this study rated the tool 4 on a 5-point scale and ranked the use of power tools (endoscopic drilling) on the 3D printed replica as 4.4. Similarly, Wurm et al[26] report participant ratings (on a 5-point scale) to be 4.8 for overall impression, 4.5 for realism and 4.4 for handling.

In the study by Tai et al[24], practicing surgeons' responses (on a 4-point scale) were 3.4, 3.3, 3.9 and 2.5 for physical attributes, realism, value

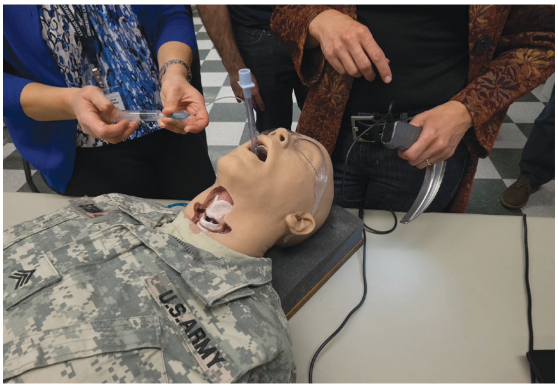

Figure 6: Prototype created by the University of Minnesota more accurately replicates human physiology.

as a simulator and global (overall). Additionally, 94% of the participants stated that the simulator was useful in its current form or with minor adjustments. For additional details, see the section "Synopses."

In comparison to cadaveric dissection, Hochman et al[16] report that 3D printing is more similar than virtual simulation in nine areas. On a 7-point scale, participants' rankings ranged from 3.5 to 5.7 for 3D printing versus 2.2 to 4.5 for virtual simulation.

In a simulated ventriculostomy, Waran et al[29] report that the burr hole procedure, including the use of a clutch-enhanced perforator, was "perfect." Overall, the participants gave a score of 4 (out of 5) for the simulated procedure.

Efficacy

The realism of the biomodels and physical simulators led the studies to conclude that 3D printing is an effective training and educational tool.

Costello et al[13] stated: "These residents demonstrated improvement in their understanding of VSDs [ventricular septal defect] … further validating the efficacy of this simulation-based educational method in the teaching of CHD [congenital heart disease]." Hochman et al[16] state that 3D printing is a superior educational tool for use in preoperative rehearsal and learning the mechanics of a procedure. This statement is backed by participant ratings of 6.2 to 7.0 (on a 7-point scale) for eight of nine domains related to the educational value of the simulator.

Ryan et al[23] used a technology acceptance model to validate 3D printing for physical simulation and found the responses suggest it is better than the status quo for ventriculostomy education.

Meanwhile, Costello et al[13] discovered that, "Pediatric residents were found to have improvement in the areas of knowledge acquisition, knowledge reporting and structural conceptualization of ventricular septal defects, as well as improvement in the ability to describe and manage postoperative complications in ventricular septal defect patients in the critical care setting."

Other Benefits

Train on a Range of Clinical Scenarios: Versus cadaveric and plastinated specimens, the studies report that 3D printing has the added value of creating multiple replicas or varying pathologies.[7,11] Once digital definitions (STL files) are secured, the specimen can be reproduced in any quantity. For cadaveric specimens and plastinated models, there is a one-to-one ratio: one cadaver for each specimen or model. This is especially important for rarer pathologies exhibited in few cadavers. With 3D printing, a unique pathology can be imaged and then shared amongst multiple institutions. For biomodels, several studies also report the advantage of enlarging the specimen to increase visibility for hard-to-see structures.[4,7,11]

Enable Single Setting, Full Procedure Training: For simulation, a key advantage of 3D printing, versus in vivo training, is the ability to complete entire procedures[24, 27, 29] in a no-risk environment. Without simulators, residents develop procedural skill in a step-wise fashion; obtaining competence in one step before advancing to the next step, at a later date on a different patient. Considering the work-hour constraints, pressure to reduce operating room costs and efforts to minimize risk to patients, the opportunities to practice in vivo can be minimal. 3D printed simulators do not suffer from these limitations, and therefore may accelerate resident training.

Easily Repeat Procedures: Chandrasekhara[3] states, "This [3D printed simulators] affords trainees the ability to repetitively perform and perhaps master the basic maneuvers that are the cornerstone of the procedure." He, however, continues, "Simulators are an adjunct to in vivo training. Training solely on a simulator cannot ensure competence in the procedure and does not obviate the need for in vivo training or proctored cases."

CONCLUSIONS

The studies' results demonstrate that 3D printing for biomodels and physical simulators can be an effective tool for training. Considering cost, realism, efficacy and positive impact on education, the authors collectively present a strong case for continued research and study, as well as implementation in today's medical training programs.

> Balestrini et al[4]: "The models produced are accurate and can represent all parts of the human anatomy, including soft tissue, at a price point that allows widespread use. 3D printing is no longer limited to those with a special interest but is evolving into a valuable teaching resource."

> Bustamante et al[12]: "The application of this technology could be expanded to create realistic, anatomically congruent models of difficult airway scenarios of almost any perceivable complexity, which then could be used as an invaluable tool in the teaching and training of management of such scenarios."

McMenamin et al[11]: "Thus we advocate 3D printed anatomical replicas not as a replacement but an adjunct to actual dissection."

Hochman et al[17]: "Strongly agree that 3D printing should be integrated into resident training programs. It is anticipated to have positive impact on skill development, operative performance, as well as trainee confidence."

Waran et al[28]: "Surgical trainees need multiple attempts to learn essential procedures. The use of these models for surgical-training simulation allows trainees to practice these procedures repetitively in a safe environment until they can master it. This would theoretically shorten the learning curve while standardizing teaching and assessment techniques of these trainees."

Longfield et al[19]: [3D printing] allows for a training experience that, until now, has not been feasible given the lack of pediatric CTB [cadaveric temporal bone] availability. Our prototype model does not replace cadaveric simulations yet, but are a large step towards generating a realistic replacement, particularly in the pediatric population, where cadaveric models do not exist."

SYNOPSES

For deeper insights, following are summaries of five scientific papers that provide information on their purposes, methods, results and conclusions.

"Endoscopic Skull Base Training Using 3D Printed Models with Pre-Existing Pathology" [20]

By Narayanan V, Narayanan P, Rajagopalan R, Karuppiah R, et al in European Archives of Otorhinolaryngol

Purpose

Assess the ease of learning endoscopic skull base exposure and drilling techniques using an anatomically accurate physical model with pre-existing pathology.

Methods

Study: Fifteen ENT surgeons were assigned to five teams, and each team was assigned a workstation that included an image guidance station (Medtronic S7, Ireland), endoscope system (Karl Storz, Germany), equipment to perform the operation, and a 3D printed model. Participants were instructed to complete key steps of the procedure and assess the simulator for image guidance, surgical procedure, anatomy accuracy and drilling.

3D printing: MRI and CT data of a patient with basilar invagination was used. The DICOM file was then imported into BIOMODROID (University of Malaya, Malyasia) where it was segmented and converted to STL format. To meet the simulation objectives, the data was further modified: anterior nasal structures were simplified and turbinates were omitted.

The 3D printed model was produced on an Objet500 Connex (Stratasys, Israel and USA) that replicated bone and soft tissue, including the septum using multi-material printing.

Results

Participants reported that their overall experiences were very favorable, especially in learning certain crucial steps like image guidance navigation and using power tools for endoscopic drilling. The low scores were limited to anterior nasal anatomy and transnasal access, both of which were not the objective of this model. The general consensus of the participants was that the model was very realistic and useful in learning a complex procedure, in a repetitive fashion with ease and safety.

Assessed on a five-point Likert scale, mean scores ranged from 2.7 to 4.4 (Table 6).

Assessment of Skull Base Model

PROCEDURE	MEAN SCORE
Image guidance	
Model registration	4.4
Landmark confirmation	4.0
Assessment of progress	4.3
Surgical procedure	
Transnasal access	3.3
Mucosal incision	3.1
Surgical anatomy accuracy/ appearance	
Nasal structures	2.7
Clivus and skull bone	4.1
C1 and odontoid peg	4.1
Dura	4.3
Drilling and odontoid peg	
Tactile feedback	4.0
High speed drill usage	4.4

Table 6: Assessment of skull base model for training (1= unsatisfactory, 3 = average, 5 = outstanding). Source: Narayanan et al.[20]

Conclusion

Narayanan et al state, "3D printed models with pathology now allow structured simulation to be conducted in a safe workshop environment where surgeons and trainees can practice performing complex procedures under the supervision of experts."

"Three-Dimensional Printing Models Improve Understanding of Spinal Fracture—A Randomized Controlled Study in China"[8]

By Li Z, Li Z, Xu R, Li M, et al in Scientific Reports

Purpose

Investigate the impact of 3D printed models on the identification of spinal fracture when compared to 2D CT images and 3D (digital) recreations.

Methods

Study: One-hundred and twenty medical students were randomized into three groups, each with roughly half male and half female participants. Each group was assigned one of three diagnostic tools: 2D CT images, 3D virtual model or 3D printed model. Students answered 10 questions regarding the spinal fractures and four evaluation questions related to content validity.

3D printing: CT data of spinal vertebrae were exported as a DICOM file, which was imported into Mimics (Materialise, Belgium) for 3D image construction. Mimics then exported an STL file used for 3D printing with material deposition technology (XYZ Printing, China).

Results

Students in the 3D printed model group were the fastest to answer the diagnostic questions, with no sex-related difference. Those in the 2D CT group took 114% (mean) more time to answer. Those in the 3D virtual model group took 46% longer.

Students in the 3D printed model group also had the highest number of correct answers (7.2 [mean] of 10) for spinal fracture diagnosis with no sex-related difference. Those in the 2D CT group had the fewest correct answers with a mean of 4.1, and those in the 3D virtual model group had 6.4 correct answers.

In the assessment of the teaching methods, students in the 3D printed model group answered more positively than those in the 2D CT and 3D virtual model groups in each of the four areas: evaluation pleasurability, teaching aid assistance, learning effectiveness and diagnosis confidence.

See the section “Results and Finding: Training outcomes” for the table of performance results.

Conclusion

Li et al state, “3D-printed models markedly improved the identification of complex spinal fracture anatomy by medical students and was equally appreciated and comprehended by both sexes. Therefore, the lifelike fracture model made by 3D printing technology should be used as a means of pre-medical education.”

“End User Comparison of Anatomically Matched 3-Dimensional Printed and Virtual Haptic Temporal Bone Simulation: A Pilot Study”[16]

By Hochman JB, Rhodes C, Kraut J, Pisa J, Unger B in Otolaryngol

Purpose

Directly compare surgical residents’ impressions of two distinct temporal bone simulations: virtual model and physical, 3D printed model.

Methods

Study: Ten resident trainees dissected (drilled) a unique cadaveric specimen and matching virtual and 3D printed models. The virtual simulator included a haptic feedback device.

Following the surgical session, subjects were then asked to complete a survey where they ranked physical characteristics, anatomical feature representation, usefulness in surgical training and perceived educational value. Subjects also directly contrasted the virtual and 3D printed simulators.

3D printing: Micro-CT (SkyScan 1176, Bruker, USA) from 10 cadaveric samples produced DICOM files that were then segmented into separate structural features using Mimics (Materialise, Belgium). To preserve void spaces, the file was split into multiple polygonal meshes that were exported as individual STL files. Each file was 3D printed separately, using binder jetting technology. After printing, the components were cleaned, infiltrated with a blend of cyanoacrylate and hydroquinone, and assembled.

Results

In the direct comparison of both simulations, participants rated the 3D printed model as superior in seven of nine domains. Anatomic features, relative to cadaveric bone, were well regarded for both simulations with no significant difference between them. Residents also generally considered both to be productive resources in acquiring surgical skill. However, they found the 3D printed model to be more educationally effective, namely in terms of the simulator being an effective training instrument, that it should be integrated into resident education and that it would improve confidence in surgery.

The most significant difference was in the comparison to the physical properties of cadaveric bone (Table 7). In each of the nine measures,

Comparison of Virtual and 3D Printed Model to Cadaveric Specimen

MODEL FACTOR	VIRTUAL MODEL	3D PRINTED MODEL
Cortical bone hardness	3.2 ± 2.0	5.5 ± 1.5
Trabecular bone hardness	2.8 ± 1.6	5.2 ± 1.3
Vibrational properties	3.2 ± 1.5	5.7 ± 0.8
Acoustic properties	2.7 ± 2.0	5.3 ± 1.2
Drill slip	2.9 ± 2.0	5.4 ± 1.4
Air cell system	4.5 ± 1.4	5.4 ± 1.4
Thinning of dural plates	3.5 ± 1.8	4.2 ± 2.0
Palpation of dura	2.2 ± 1.6	3.4 ± 1.8
Overall similarity to cadaveric temporal bone	3.5 ± 1.8	5.9 ± 0.7

Table 7: Mean comparison rating and standard deviation using 7-point scale (7 = very similar). Source: Hochman et al.[16]

the 3D printed model was found to be more comparable to a cadaveric specimen, with mean values ranging from 3.4 to 5.9 (on a seven-point Likert scale). The virtual model had mean values of 2.2 to 4.5.

Conclusion

Hochman et al state, “Appraisal of a PBM [3D printed simulation] and a VM [virtual simulation] found both to have perceived educational benefit. However, the 3D-printed model was considered to have more realistic physical properties and was considered to be the most effective and preferred training instrument.”

Note: The authors completed a similar study[17] comparing 3D printed models to cadaveric specimens that had results aligned with those reported above.

“Development of a 3D-Printed External Ventricular Drain Placement Simulator: technical note”[24]

By Tai BL, Rooney D, Stephenson F, Liao PS, et al in Journal of Neurosurgery

Purpose

Assess a physical model developed to simulate accurate external ventricular drain (EVD) placement with realistic haptic and visual feedback to serve as a platform for complete procedural training.

Methods

Study: Seventeen neurosurgeons from three Michigan-based neurological training programs (University of Michigan, Wayne State University and Henry Ford Hospital) completed the EVD procedure at their own institutions. Using the simulator, participants performed the entire skin-to-skin EVD placement procedure, including tunneling and suturing.

After completing the procedure, the participants completed a survey, rating 37 items on a 4-point scale. Nineteen of the items targeted simulator characteristics and features organized in four domains: physical attributes, realism of experience, simulator value and global (overall) rating.

3D printing: simulator (Figure 7) consisted of a skull frame, skull cap, replaceable insert and brain phantom. The insert, which has an artificial scalp placed on it, is replaced after each procedure.

The geometry of the simulator originated from CT scans, and the data was modified to include fastening features for assembly (Mimics, Materialise, Belgium).

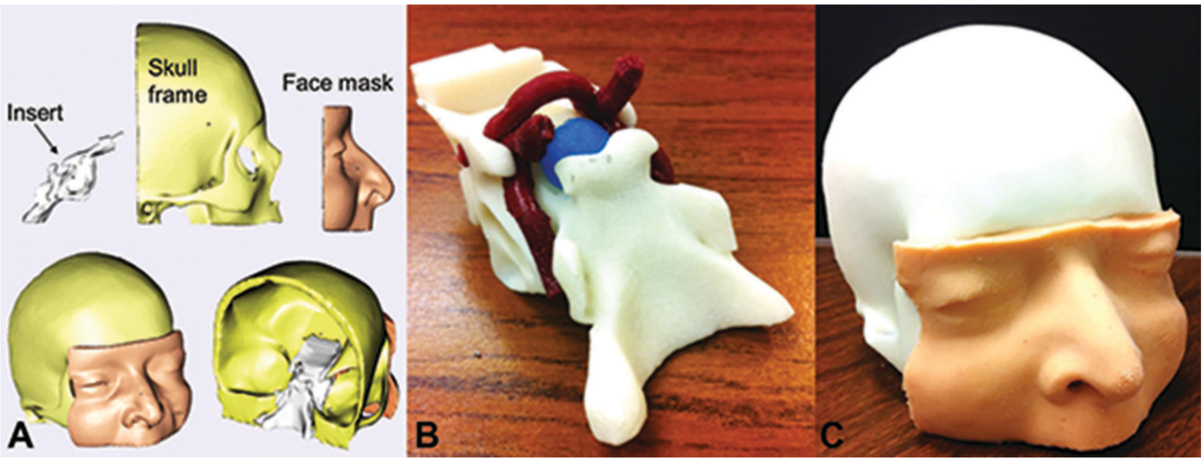

Figure 7: From Tai et al, design of the endoscopic endonasal approach drilling simulator computer model (A), prototype insert (B), and prototype skull frame and face mask (C).

The skull frame and cap were 3D printed in ABS plastic using material deposition technology (unnamed). These were used without further modification. The insert was 3D printed in a plaster composite material using binder jetting technology (unnamed). After printing the insert was treated with an epoxy resin to create biocortical characteristics. Then artificial galea and dura were applied, followed by a layer of silicone scalp material.

The phantom brain was cast in a high-acyl gellan gum to create a realistic texture and mimic biomechanical properties of brain tissue. The mold for the casting was 3D printed (material and technology unnamed). To create pressure within the brain phantom and to offer the sensation of "popping" when penetrated with a catheter, it was filled with water. Pressure was controlled by a water reservoir located above, and attached to, the ventricle.

Results

Participating surgeon responses showed average ratings of 3.4, 3.3, 3.9, and 2.5 (on a 4-point scale) for physical attributes, realism of experience, value of the simulator as a training tool, and global (overall) domains, respectively (Table 8). The highest score of 3.9 was obtained for "value of simulator as a training tool for novice neurosurgeons."

Six participants (35.3%) indicated the simulator was useful in its current form but could be slightly

Neurosurgeon Rating of 3D Model

SURVEY ITEMS	MEAN SCORE (SD)
Physical attributes	3.4
Scalp	3.1 (0.44)
Bone	3.4 (0.62)
Dura thickness	2.9 (0.71)
Brain tissue texture	3.4 (0.72)
Visualization of skull landmarks	3.0 (0.72)
Location of insert for drilling	3.6 (0.50)
Size of the insert for drilling	3.9 (0.47)
CSF flow (rate) to confirm placement	3.6 (0.77)
Realism of experience	3.3
Identifying skull landmarks	3.2 (0.55)
Incision and retraction of skin	3.1 (0.87)
Drilling bone	3.3 (0.84)
Opening dura	2.6 (0.95)
Inserting ventriculostomy	3.3 (0.69)
Water flowing from catheter & visual confirmation of trajectory	3.4 (0.79)
Tunneling of ventriculostomy	3.4 (0.62)
Placement of retaining stitches	3.7 (0.50)
Scalp closure	3.5 (0.52)
Value of simulator as a training tool	3.9 (0.25)
Global rating	2.5 (0.48)

Table 8: Survey results from 17 experienced neurosurgeons and residents (4-point scale). Source: Tai et al.[24]

improved. Ten (58.8%) indicated the simulator requires minor adjustments before it can be considered for use.

Conclusion

Study results strongly support the use of this model for EVD training. Participants found that the simulator provides realistic haptic feedback during a procedure, with visualization of catheter trajectory and fluid drainage.

Tai et al state, “With minor refinement, this simulator is expected to improve training experiences in neurosurgery, thereby leading to better patient care.” The authors also state, “Following the recommended refinements and future study, the simulator is expected to be incorporated into a comprehensive curriculum to train residents in EVD placement.”

Note: The lead author completed a similar study[25] on a simulator for endoscopic endonasal drilling using the same structure. Results were comparable.

“Incorporating Three-dimensional Printing into a Simulation-based Congenital Heart Disease and Critical Care Training Curriculum for Resident Physicians”[13]

By Costello JP, Olivieri LJ, Su L, Krieger A, et al in Congenital Heart Disease

Purpose

Evaluate whether heart models created with 3D printing technology can be effectively incorporated into a simulation-based congenital heart disease and critical care training curriculum for pediatric resident physicians.

Methods

Study: A simulation-based educational curriculum, which used 3D printed heart models, providing instruction on the anatomy and clinical management of ventricular septal defects (VSD) for pediatric residents was developed and conducted in interactive, hands-on seminars. Twenty-three pediatric residents (interns through chief residents) voluntarily participated in one of two teaching seminars.

At the conclusion of the training, each participant completed a questionnaire that examined three educational elements: knowledge acquisition, knowledge reporting and structural conceptualization of VSDs.

3D printing: DICOM data of five common VSD subtypes were obtained from a radiology archive. The data was analyzed and segmented in Mimics (Materialise, Belgium) to create STL files of the heart. Further processing was completed in 3-matic (Materialise). The digital heart models were 3D printed with an Objet500 Connex (Stratasys, Israel and USA). The resultant models had properties that allowed for surgical incisions and suturing.

Results

Self-reported values for pre- and post-seminar learning categories showed significant improvement in all measured areas.

The residents benefited in terms of knowledge acquisition of VSDs from the simulation training. There were also improvements in the ability of the residents to report on the knowledge of VSDs that they obtained during the simulation seminars. The residents' proficiency in conceptualizing the structure of VSDs was also found to be enhanced (Table 9).
The residents also reported improvement in their ability to describe and manage postoperative complications in VSD patients in the critical care setting.

Study Results for Pre- and Post-Seminar Knowledge

LEARNING CATEGORIES	PRE-SEMINAR SCORE	POST-SEMINAR SCORE
Knowledge acquisition	4.83	7.33
Knowledge reporting	4.25	6.86
Structural conceptualization	4.17	7.22

Table 9: 10-point scale. Source: Costello et al.[13]

Conclusion

Costello et al state, "3D printing in a simulation-based congenital heart disease and critical care training curriculum is feasible and improves pediatric resident physicians' understanding of a common congenital heart abnormality." The authors continue, "Further utilizing this technology for education and training in the clinical setting is not only feasible but also potentially beneficial to health care providers beyond resident physicians."

LIMITATIONS AND CONSIDERATIONS

As noted previously, there are limitations when 3D printing is used to fabricate medical replicas. However, these constraints are shared with all other training tools that are adjuncts to cadaveric dissection or in vivo practice. Additionally, several important considerations are related to the studies themselves, not the process of 3D printing.

The studies were structured to assess face or content validity and used small sample sizes, with just 12 having 10 or more participants. While the results are promising, there is a limited body of evidence to confirm the efficacy as a training tool. Additionally, there are few studies, of any scale, that compare the educational efficacy and efficiency of 3D printed replicas to traditional educational methods.

In domains where participants ranked the 3D printed replicas as less than satisfactory, the root cause was frequently the digital input to the 3D printer. Simply put, output quality is tied to digital model design quality.[7,10] For example, the accuracy of a 3D printed model can be no better than the resolution of a CT scan. Additionally, the process of segmentation and data manipulation will affect the quality. There were several instances where unsatisfactory ratings were given for structures that were not viewed as important to the studies (therefore less effort was applied to produce good input) or were manipulated in a way that participants deemed undesirable.

With regards to 3D printing, the most cited limitation is material properties, especially for soft tissues.[20,22,25] As Mashiko et al[22] state, "Further technical advances are needed in this area." It is important to note, however, that the limitation in material characteristics is also true for non-3D printed materials (e.g., materials cast into 3D printed molds) and that 74% of all anatomic structures were printed with single-material technologies, many that required the addition of infiltrants, coatings and synthetic simulants. Taking advantage of newer technology that enables a large number of materials and colors to be combined in a single 3D print may satisfy some of these issues.

Material properties must advance, yet the limitations of 3D printing are shared by commercial synthetic models and plastinated specimens, and to a lesser degree, cadaveric specimens. To approach a perfect simulation, 3D printers must advance such that they can reproduce the anisotropic properties and structures of all tissues; from the subtle variation in the brain to the variations between compact and spongy bone.

The perfect simulation would also have 3D printed replicas that match the visual characteristics of the human anatomy, namely color and texture. And according to Narayaman et al[20], blood and cerebrospinal fluid, factors that make surgery vivid and challenging, are desirable.

CONCLUSION

Studied across multiple domains, spanning efficacy, realism and value, the consensus is that 3D printing, for static biomodels and physical simulators, is a comparable or superior alternative to traditional educational and training tools. 3D printing addresses the limitations of these conventional methods and can be employed to expand access to hands-on learning, while minimizing the risks associated with training in the operating theater, and improve skill levels for complex procedures.

The studies unanimously conclude that 3D printing is a viable and potentially effective alternative for education and training of medical students, residents, fellows and practicing doctors. With large-scale studies, warranted by the authors' content validation studies, the potential may be confirmed. It is anticipated that such studies will reveal that 3D printing has a positive impact on skill development, operative performance and trainee confidence.

The primary limitation of 3D printing, physical properties of its materials, is also its greatest opportunity. With advancement in this area, 3D printing has the potential to be a superior solution for providing realistic, tactile feedback for all tissues. When these advanced materials are deployed on multi-material 3D printers, structures and physical properties that are anisotropic may be concurrently printed for multiple tissue types.

As Waran et al[27] state, "The use of the new-generation 3D printer yields the creation of more realistic models with multiple tissues, which allows an improved training experience. As 3D printer technology improves, these machines will provide the possibility for newer, more complex models to be created, allowing an improved training experience. In the future it may be possible to simulate the handling characteristics of brain parenchyma itself, allowing trainees to perform actual dissection and retraction."

The advancements in 3D printing technologies and materials will likely lead to innovations in anatomical models and simulator design. Leveraging 3D printing's ability to replicate negative air space, fluids and gases may be added to enhance the realism of the physical simulator. Mimicking the pulsation of blood flow or the pressure delta during respiration, 3D printed simulators may be discovered to be more than an adjunct to cadaveric dissection. When sophisticated sensors are embedded in those replicas, the simulation can be adjusted and monitored for any patient type and any pathology; and the trainee's performance can be evaluated.

The last noted limitation is cost. Although viewed as cost effective relative to traditional methods, several studies note that cost reductions, both in 3D printed model cost and 3D printers, are desirable to expand use of the technology within medical training programs.

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