 doi:10.20944/preprints202012.0772.v1

Brief Report

Mesh-type 3D printing of human organs and tumors: fast, cost-effective, and personalized anatomic modeling of patient-oriented visual aids

Running title: Mesh-type 3D printing of human organs and tumors

Jungirl Seok, MD[1,2], Sungmin Yoon[3], Chang Hwan Ryu, MD, PhD[1], Junsun Ryu, MD, PhD[1], Seok-ki Kim, MD, PhD[4,*] and Yuh-Seog Jung, MD, PhD[1,*]

[1]Department of Otorhinolaryngology-Head and Neck Surgery, National Cancer Center, Goyang-si, Republic of Korea
[2]Department of Biomedical Engineering, College of Medicine, Seoul National University, Seoul, Republic of Korea
[3]Division of Convergence Technology, [4]Department of Nuclear Medicine, National Cancer Center, Goyang-si, Republic of Korea
*Authors contributing equally to this work
* Correspondence: **Authors at: Yuh-Seog Jung, MD, PhD** Dept. of Otorhinolaryngology-Head and Neck Surgery, National Cancer Center, 323 Ilsan-ro,Ilsandong-gu, Goyang-si, Gyeonggi-do, 10408, Republic of Korea Tel: +82-31-920-1685, Fax: +82-31-920-2799, E-mail: jysorl@ncc.re.kr
Seok-ki Kim, MD, PhDDept. of Nuclear Medicine, National Cancer Center, 323 Ilsan-ro,Ilsandong-gu, Goyang-si, Gyeonggi-do, 10408, Republic of KoreaTel: +82-31-920-1731, Fax: +82-31-920-2799, E-mail: skkim@ncc.re.kr

Abstract**:** Although 3D-printed anatomic models are not new to medicine, the high costs and lengthy production times entailed have limited their application. Our goal was developing a new and less costly 3D modeling method to depict organ-tumor relations at faster printing speeds. We have devised a method of 3D modeling using DICOM images. Coordinates are extracted at a specified interval, connecting them to create mesh-work replicas. Adjacent constructs are depicted by density variations, showing anatomic targets (ie, tumors) in contrasting color. An array of organ solid-tumor models were printed via Fused Deposition Modeling 3D printer at significantly less cost ($0.05/cm^3) and time expenditure (1.73 min/cm^3; both, p<.001). Printed models helped promote visual appreciation of organ-tumor anatomy and adjacent tissues. Our mesh-work 3D thyroidal prototype reproduced glangular size/contour and tumor location, readily approximating the surgical specimen. This newly devised mesh-type 3D printing method may facilitate anatomic modeling for personalized care and improve patient awareness during informed surgical consent.

Keywords: 3D printing; anatomic modeling; personalized medicine

 doi:10.20944/preprints202012.0772.v1

1. Introduction

To obtain patient consent for an operation, the nature of the procedure must be explained, as well as expected benefits and potential risks or adverse effects, alternative treatment options, and likely outcomes if surgery is declined [1]. Appropriate and well-documented informed consent is mandatory to preclude civil action for negligence or otherwise protect medical staff from legal conflicts [2,3]. Unfortunately, attempts to convey the fundamentals of intended procedures sometimes fail, depriving patients of proper working knowledge for granting consent [4]. There are reports that visual aids used to supplement verbal descriptions allow better conceptualization and processing of the information delivered [5,6]. Three-dimensional (3D) models, in particular, may depict the visual aspects of procedures more effectively. Recently, 3D printers have been studied expressly for this purpose [7-9].

3D-printed anatomic models are widely used in surgical fields, particularly in orthopedic and maxillofacial specialties, as operative guides or templates for surgical planning, implant design, molding of prosthetics, and patient selection [10]. They have also been an asset in patient education [7,8]. Personalized 3D models that replicate actual organ or tissue conditions may aid in evaluating disease states and help expedite preoperative preparations [11]. However, such models have not yet proven cost-effective, the expense and time invested acknowledged as shortcomings [7,8,10].

The present study was undertaken to preliminarily investigate a mesh-type 3D modeling technique for solid tumors that effectively reduces cost and printing time, without loss of organ-tumor anatomic relations.

2. Methods

2.1. Ethical considerations

The institutional review board at the National Cancer Center, Republic of Korea approved our study protocol (IRB No. NCC2020-0248). No patient data was collected, so required informed consent was waived.

2.2. Personalized mesh-type 3D modeling and two-color 3D printing

Our newly devised modeling method is intended to limit unnecessary input while ensuring the accuracy of organ-tumor anatomic depictions. Normal structures are portrayed in one color (ie, white) as differing mesh densities, with tumors shown in sharply contrasting hue (ie, blue) (**Figure 1**).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 31 December 2020 doi:10.20944/preprints202012.0772.v1

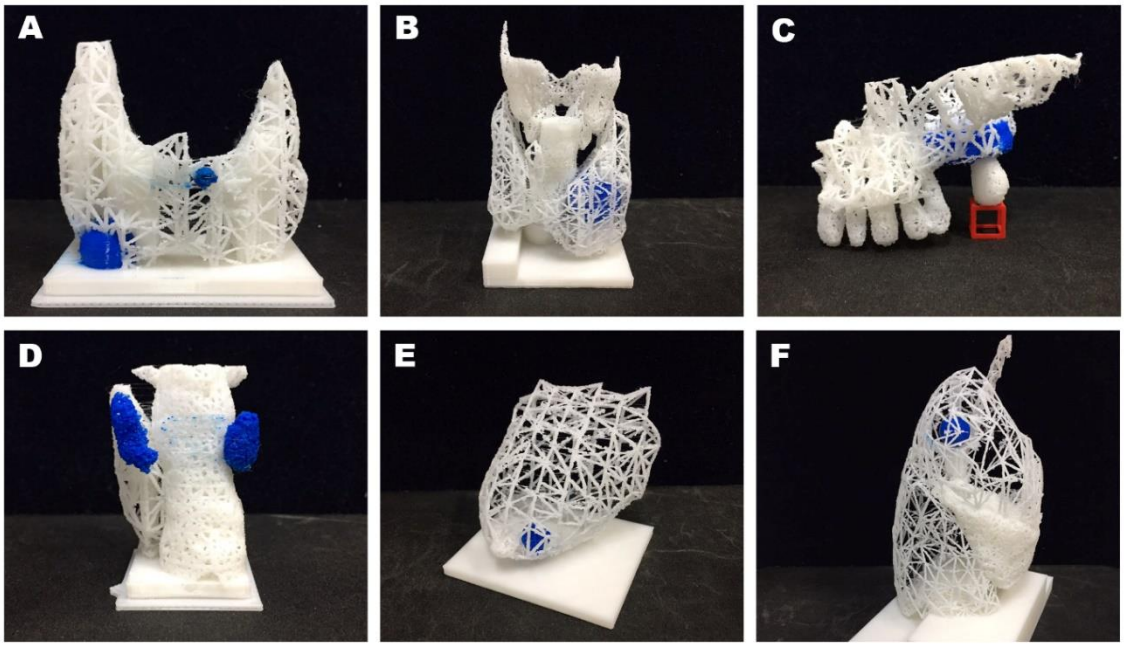

Figure 1. Examples of mesh-type 3D modeling: (**a**) Tumor of thyroid gland; (**b**) thyroid gland and adjacent cartilage; (**c**) maxillary tumor (lateral view); (**d**) parathyroid adenoma (posterior view); (**e**) breast tumor; and (**f**) right lung nodule (lateral view). Note: each tumor printed in blue, adjacent structures shown as differing mesh densities.

The segmentation of organs and tumors in DICOM images may be done manually or using deep learning techniques [12]. To confirm the feasibility of this mesh-type 3D modeling, we prepared images through manual segmentation. A segmented area or 'mask' was expressed as a 2-dimensional array in programming language. Masks were then stacked to build 3D arrays and resampled to reflect actual sizes, based on original pixel spacing and slice thickness. The final step was the marking of tumor locations and areas. All 3D arrays were subsequently reconfigured to 3D representations in triangular meshes, using the Trimesh package (v2.38.24) in Python language [13]. After smoothing, the density of every structure was set by stipulating one vertex per designated area (eg, 4.5 mm^2). Using the PyQt5 library (v5.15.0, Riverbank Computing Ltd, Dorchester, UK), an application capable of handling the entire process was invoked to do so (**Figure 2**). Such vertex/facet restrictions enabled completion of our mesh-type 3D models.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 31 December 2020 doi:10.20944/preprints202012.0772.v1

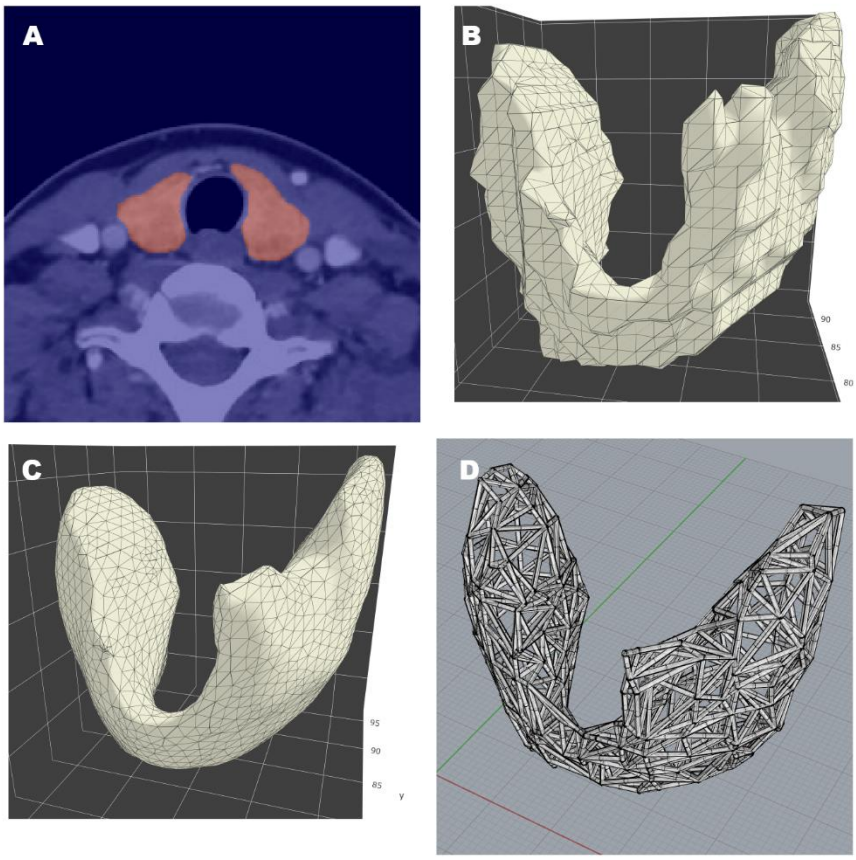

Figure 2. Thyroidal prototype of mesh-work 3D modeling: (**a**) segmentation of thyroid gland in tomographic image; (**b**) reconstruction via triangular mesh; (**c**) surface smoothing; (**d**) resultant 3D model.

We engaged a two-color 3D printer (3DWOX 2X; Sindoh, Seoul, Republic of Korea) and its slicer software (3DWOX Desktop; Sindoh) for model fabrication. This printer works in Fused Deposition Modeling (FDM) mode, extruding polylactic acid (PLA) as the material of choice. Ultimately, we confirmed the clinical potential of a 3D-printed thyroidal prototype by comparing it with the corresponding thyroidectomy specimen.

3. Results

Several organ-tumor models were printed in this manner (**Figure 1**). By varying mesh densities, disparate structures were distinguishable as follows: thyroid lobe and trachea (**Figure 1c**), maxillary bone and teeth (**Figure 1d**), breast and nipple (**Figure 1e**), and the three lobes of right lung (**Figure 1f**). The mesh style is indicative of tumor occupancy in 3D (even if inside solid organs), without the need of transparent material.

Printed dimensions (relative to actual size), printing time, post-processing time, and cost were evaluated in each organ-tumor model (**Table 1**). Post-processing time was spent removing model support structures that the slicer program automatically applied. Both printing time and cost significantly correlated with 3D model size: 1.73 min/cm^3 (p<.001) and \$0.05/cm^3 (p<.001).

Table 1. Specifications, production times, and costs of various mesh-type 3D models.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 31 December 2020 doi:10.20944/preprints202012.0772.v1

Model	Dimensions (cm)	Relation to actual size	Printing time	Post-processing time (min)	Cost
Thyroid tumor	5.3 x 3.0 x 6.5	1	2 h 50 m	10	$2.72
Thyroid gland and adjacent cartilage	5.5 x 4.3 x 9.3	1	9 h 15 m	10	$8.69
Maxillary tumor	7.1 x 5.7 x 4.7	1	9 h 4 m	15	$8.24
Parathyroid adenoma	4.0 x 3.1 x 5.5	1	5 h 3 m	10	$3.71
Breast tumor	6.2 x 5.2 x 5.9	½	6 h 41 m	5	$7.78
Lung nodule	6.8 x 8.0 x 13.5	½	23 h 4 m	40	$33.67

We also compared a 3D-printed model of thyroid gland with the actual thyroidectomy specimen, shown in **Figure 3.** There was no observed disparity in glandular size or contour. The model and surgical specimen also corresponded well in terms of tumor location.

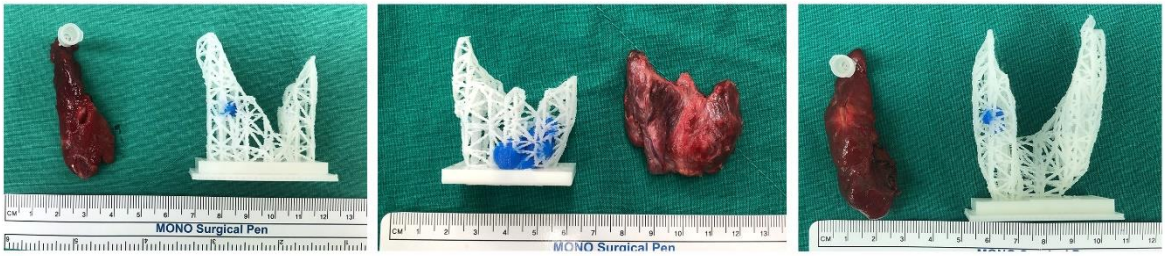

Figure 3. Side-by-side comparison of 3D-printed thyroidal prototype and corresponding surgical specimen.

4. Discussion and Conclusion

4.1. Discussion

In the context of tumors, adequate information and understanding conveyed to a competent patient provides a sound basis for voluntary and rational decision-making [14]. Thus, the primary goal of informed surgical consent is establishing a rudimentary appreciation of key principles, including organ anatomy, physiology, and attributes; tumor location; and potential operative complications [7]. In portraying a solid tumor, capsular breech and invasion of surrounding tissues are other important considerations that a 3D model effectively addresses. A personalized model rendered by 3D printer reinforces the mutual sense of awareness needed between patient and physician [7]. Only a few studies to date have tested 3D models in patients facing thoracic, kidney, or orthopedic surgeries, but they have regularly shown improved preoperative understanding or satisfaction [7-9]. Still, a number of issues pertaining to cost, resolution and duration of printing, and material texture must be resolved before 3D-printed models become more mainstream [11].

Our novel methodology offers several advantages. The customary segmentation of targeted objects entailed in 3D reconstruction of tomographic images is readily applicable to mesh-type 3D modeling. Hence, newer CT systems are not required, and routine CT protocols for specific organs may be utilized. Likewise, an expensive 3D printer is not essential. Even if just two colors are available, organs or organ parts may be printed differentially by merely changing mesh densities. Filament requirements

 doi:10.20944/preprints202012.0772.v1

(and thus costs) are similarly reduced because the printed organs are largely empty inside. Given a magnitude ≤10 cm, most models were fabricated within half a day. Thus, the day after computed tomography or magnetic resonance imaging studies are obtained, completed models are feasible.

There is some concern that mesh-type 3D modeling results do not accurately reflect the organs or the tumors they represent. However, further attempts at refinement may nevertheless impose unwanted steps. For example, CT imaging at 1-mm slice thickness (vs routine setting) as a means of enhancing replication demands higher radiation exposure. Although not statistically proven, the size and contour of a printed thyroid gland and the tumor situated within it satisfactorily mimicked attributes of the corresponding surgical specimen, confirming this approach as a viable tool for personalized care.

With regard to study limitations, PLA output is clearly of low quality, lacking sophistication [15]. Stringing may also develop as a technical issue, although this is avoidable by controlling printer settings or resorting to non-FDM 3D printing techniques. We could not pursue internally filled models (delineating tumors) to compare costs and printing times, because no transparent or translucent PLA filament was compatible with our printer; and even half-size printing of a large organ (such as lung) called for nearly an entire day. Overall, our model depicts actual organ size and tumor location at low levels of resolution. To truly establish its merit, prospective research is needed.

4.2. Conclusion

We have devised a mesh-type 3D modeling technique involving less cost and faster completion than full 3D printing efforts. This approach may facilitate the fabrication of anatomic models for personalized care, helping patients to conceptualize various organs, tumors, and surrounding tissues during informed surgical consent.

Ethics approval and participant consent: The institutional review board at the National Cancer Center, Republic of Korea approved our study protocol (IRB No. NCC2020-0248). No patient data was collected, so required informed consent was waived.

Consent for publication: All authors have agreed to publication of this article.

Availability of data and material: The models and their source files bear the personal medical information of patients studied and cannot be provided under domestic regulation.

Competing interests: JG: CHR, JR, and YSJ are listed on a patent application describing similar methodology and filed by the National Cancer Center of Korea (application no. 10-2020-0000849; filed 03 January 2020). No other authors have conflicts of interest to declare.

Funding: This study was supported by a grant from the National Cancer Center in Korea [grant Nos. NCC2031580-1 and NCC2010241]. The authors have no financial ties to disclose.

Credit authorship contribution statement: Jungirl Seok: Formal analysis, funding acquisition, and writing of original draft. Sungmin Yoon: Data curation and writing of original draft. Chang Hwan Ryu: Data curation and writing of original draft. Junsun Ryu: Data curation and writing of original draft. Seok-ki Kim: Conceptualization, methodology and revising original draft. Yuh-Seog Jung: Conceptualization, funding acquisition, project administration, review and editing of manuscript.

References

1. Hanson M, Pitt D. Informed consent for surgery: risk discussion and documentation. Can J Surg. 2017;60(1):69-70.
2. Mishra PK, Ozalp F, Gardner RS, Arangannal A, Murday A. Informed consent in cardiac surgery: is it truly informed? J Cardiovasc Med. 2006;7(9):675-81.
3. Villanueva C, Talwar A, Doyle M. Improving informed consent in cardiac surgery by enhancing preoperative education. Patient Educ Couns. 2018;101(12):2047-53.
4. Tait AR, Voepel-Lewis T. Digital multimedia: a new approach for informed consent? JAMA. 2015;313(5):463-4.
5. Rosenfeld EH, Lopez ME, Yangyang RY, et al. Use of standardized visual aids improves informed consent for appendectomy in children: A randomized control trial. Am J Surg. 2018;216(4):730-5.
6. Moseley TH, Wiggins MN, O'sullivan P. Effects of presentation method on the understanding of informed consent. Br J Ophthalmol. 2006;90(8):990-3.
7. Bernhard JC, Isotani S, Matsugasumi T, Duddalwar V, Hung AJ, Suer E, et al. Personalized 3D printed model of kidney and tumor anatomy: a useful tool for patient education. World J Urol. 2016;34(3):337–45.
8. Yoon SH, Park S, Kang CH, Park IK, Goo JM, Kim YT. Personalized 3D-Printed Model for Informed Consent for Stage I Lung Cancer: A Randomized Pilot Trial. In: Seminars in Thoracic and Cardiovascular Surgery. Elsevier; 2019. p. 316–8.
9. Zhuang Y, Zhou M, Liu S, Wu J, Wang R, Chen C. Effectiveness of personalized 3D printed models for patient education in degenerative lumbar disease. Patient Educ Couns. 2019;102(10):1875-81.
10. Tack P, Victor J, Gemmel P, Annemans L. 3D-printing techniques in a medical setting: A systematic literature review. Biomed Eng Online. 2016;15(1):115.
11. Yan Q, Dong H, Su J, Han J, Song B, Wei Q, et al. A Review of 3D Printing Technology for Medical Applications. Engineering. 2018;4(5):729–42.
12. Hesamian MH, Jia W, He X, Kennedy P. Deep learning techniques for medical image segmentation: Achievements and challenges. J Digit Imaging. 2019;32(4):582–96.
13. Dawson-Haggerty et al. trimesh [Internet]. Available from: https://trimsh.org/
14. Lidz CW. The therapeutic misconception and our models of competency and informed consent. Behav Sci Law. 2006;24(4):535-46.
15. Garcia J, Yang ZL, Mongrain R, Leask RL, Lachapelle K. 3D printing materials and their use in medical education: A review of current technology and trends for the future. BMJ Simul Technol Enhanc Learn. 2018;4(1):27–40.

 doi:10.20944/preprints202012.0772.v1

Notes on Contributors:

JUNGIRL SEOK, M.D., is a clinical staff of the Department of Otorhinolaryngology-Head and Neck Surgery, National Cancer Center, Goyang-si, Republic of Korea. He is studying for Ph.D. in the Department of Biomedical Engineering, College of Medicine, Seoul National University, Seoul, Republic of Korea. His research interests include integrative medical research.

SUNGMIN YOON, is a research technician in the Division of Convergence Technology, National Cancer Center, Goyang-si, Republic of Korea. His research interests include 3D printing and artificial intelligence.

CHANG HWAN RYU, M.D, Ph.D., is a clinical staff and senior researcher of the Department of Otorhinolaryngology-Head and Neck Surgery, National Cancer Center, Goyang-si, Republic of Korea**.** His research interests include head and neck cancer, robotic surgery, and laryngology.

JUNSUN RYU, M.D, Ph.D., is a clinical staff and senior researcher of the Department of Otorhinolaryngology-Head and Neck Surgery, National Cancer Center, Goyang-si, Republic of Korea**.** His research interests include thyroid cancer, robotic surgery, and molecular biology.

SEOK-KI KIM, M.D, Ph.D., is a clinical staff and senior researcher of the Department of Nuclear medicine, National Cancer Center, Goyang-si, Republic of Korea**.** His research interests include thyroid cancer, optical therapy, 3D printing and biomedical engineering.

YUH-SEOG JUNG, M.D, Ph.D., is a clinical staff and senior researcher of the Department of Otorhinolaryngology-Head and Neck Surgery, National Cancer Center, Goyang-si, Republic of Korea**.** His research interests include head and neck cancer, robotic surgery, genetic and translational research.