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Geometric Evaluation of Patient-Specific 3D Bolus from 3D Printed Mold and Casting Method for Radiation Therapy

Hyun Joon An[1,2], Myeong Soo Kim[1,2], Jiseong Kim[1,2], Jaeman Son[1,2], Chang Heon Choi[1,2,3], Jong Min Park[1,2,3,4], Jung-in Kim[1,2,3]

[1]Department of Radiation Oncology, Seoul National University Hospital, [2]Biomedical Research Institute, Seoul National University Hospital, [3]Institute of Radiation Medicine, Seoul National University Medical Research Center, Seoul, [4]Robotics Research Laboratory for Extreme Environments, Advanced Institutes of Convergence Technology, Suwon, Korea

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Corresponding author
Jung-in Kim
(madangin@gmail.com)
Tel: 82-2-2072-3573
Fax: 82-2-3410-2619

Purpose: The objective of this study is to evaluate the geometrical accuracy of a patient-specific bolus based on a three-dimensional (3D) printed mold and casting method.

Materials and Methods: Three breast cancer patients undergoing treatment for a superficial region were scanned using computed tomography (CT) and a designed bolus structure through a treatment planning system (TPS). For the fabrication of patient-specific bolus, we cast harmless certified silicone into 3D printed molds. The produced bolus was also imaged using CT under the same conditions as the patient CT to acquire its geometrical shape. We compared the shapes of the produced bolus with the planned bolus structure from the TPS by measuring the average distance between two structures after a surface registration.

Results and Conclusions: The result of the average difference in distance was within 1 mm and, as the worst case, the absolute difference did not exceed ±2 mm. The result of the geometric difference in the cross-section profile of each bolus was approximately 1 mm, which is a similar property of the average difference in distance. This discrepancy was negligible in affecting the dose reduction. The proposed fabrication of patient-specific bolus is useful for radiation therapy in the treatment of superficial regions, particularly those with an irregular shape.

Keywords: Bolus, Patient specific bolus, 3D printing, Dose build up, Geometric analysis

Introduction

In radiation therapy, the primary goal is to deliver a sufficient amount of radiation to the target tumor while alleviating the effects on the adjacent normal tissue. When the planning target volume (PTV) is located near the surface area, a bolus composed of a tissue-equivalent material is used to provide an adequate dose build-up in the skin. A variety of boluses including simple water, mixtures, wax, and even metal have been used for clinical application.[1)] In most cases, a gel-sheet type bolus such as Superflab (Radiation Product Design, Albertvile, MN) is typically used to cover large areas of the skin without modification. The effects of a bolus on the surface sufficiently increase the dose for the tangential fields of conventional and intensity modulated radiation therapy (IMRT).[2)] However, under certain conditions, such as when the skin presents a particularly irregular shape, it is difficult to avoid air gaps between the bolus and the patient's skin. According to Butson et al., the effects of small air gaps of less than 2 mm under a bolus material have not been shown to reduce the surface dose. As the air gap increases by 4 mm, the surface dose decreases, and by 10 mm, up to a 10% reduction is achieved.3) Therefore, an accurate fit of the bolus to the patient's surface is important to an accurate dose delivery in near-surface tumors.

With significant advances in three-dimensional (3D) printer technologies, several studies have applied the concept of 3D-printed boluses. Kim et al. designed and fabricated a customized 3D printed bolus for a RANDO phantom, and Su et al. investigated optimizing a 3D printing bolus design for electron radiation therapy.4,5) Park et al.6) showed a reduction of the air gap compared to a commercial bolus when using a 3D-printed bolus. Ricotti et al.7) described modulating the shift of the build-up region by tuning the infill percentage of the 3D printed bolus. Beyond the phantom study, some studies have demonstrated the usefulness of 3D-printed boluses in actual patient treatment.8,9) Each of these studies was conducted using a direct 3D printing thermoplastic filament such as acrylonitrile butadiene styrene (ABS) or polylactic acid (PLA). However, these materials have a problem in that they are not fitted to the patient's surface owing to the hardness characteristics. In order to avoid the air gap, ultrasound gel can be applied to the interface between the 3D-printed bolus and the skin,10) but the gel can flow along the irregular surface or it is difficult to use it for patients with skin ulcer or bleeding. Although 3D printable flexible materials have recently been made commercially available, such as NinjaFlex, Cheeta (both from NinjaTek, Manheim, PA), TangoPlus (Stratasys, Eden Prairie, MN), they still have a solid property.

In this study, we propose a different way of fabricating a patient-specific bolus from a 3D printed mold and using a casting method. The bolus was fabricated using a more flexible and soft material and analyzed for the geometrical changes during the molding and casting process.

Materials and Methods

1. CT acquisition of patients

For this study, we chose three breast cancer patients who required a bolus to treat a superficial region. Each patient was CT scanned using a Philips Brilliance CT Big Bore (Philips Healthcare, Cleveland, OH). All reconstructed CT images had a slice thickness of 3 mm and 1.15 mm in the x- and y-axis resolution. The retrospective use of the scan data was approved by the Institutional Review Board of our institute.

2. Bolus structure from planning system

Based on the acquired CT images, the bolus was designed using an Eclipse (Varian Medical Systems, Palo Alto, CA) treatment planning system (TPS). The external surface of the patient body was defined using automatic body contouring. A 10-mm thick bolus was added outside the external surface to include the planning target volume (PTV) area. The thickness was manually changed in some areas to closely adhere to the patient's body, as shown in Fig. 1.

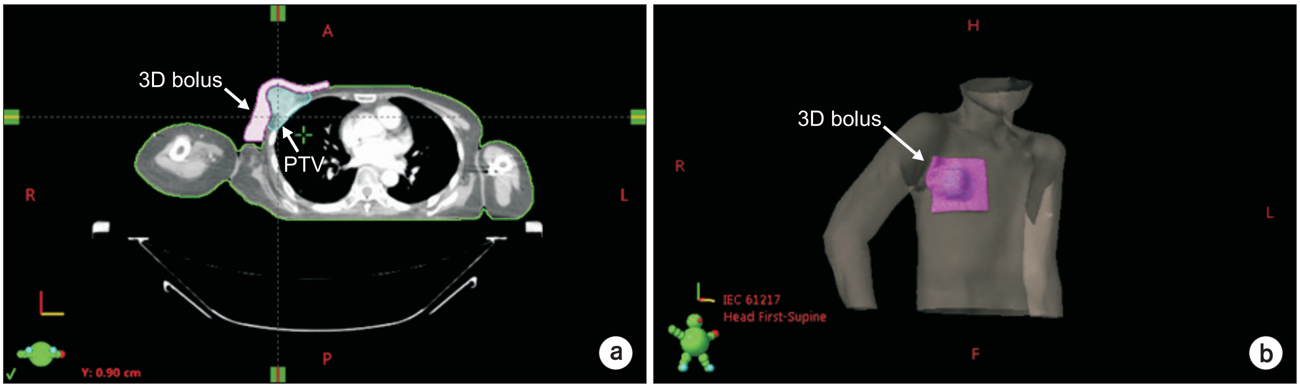
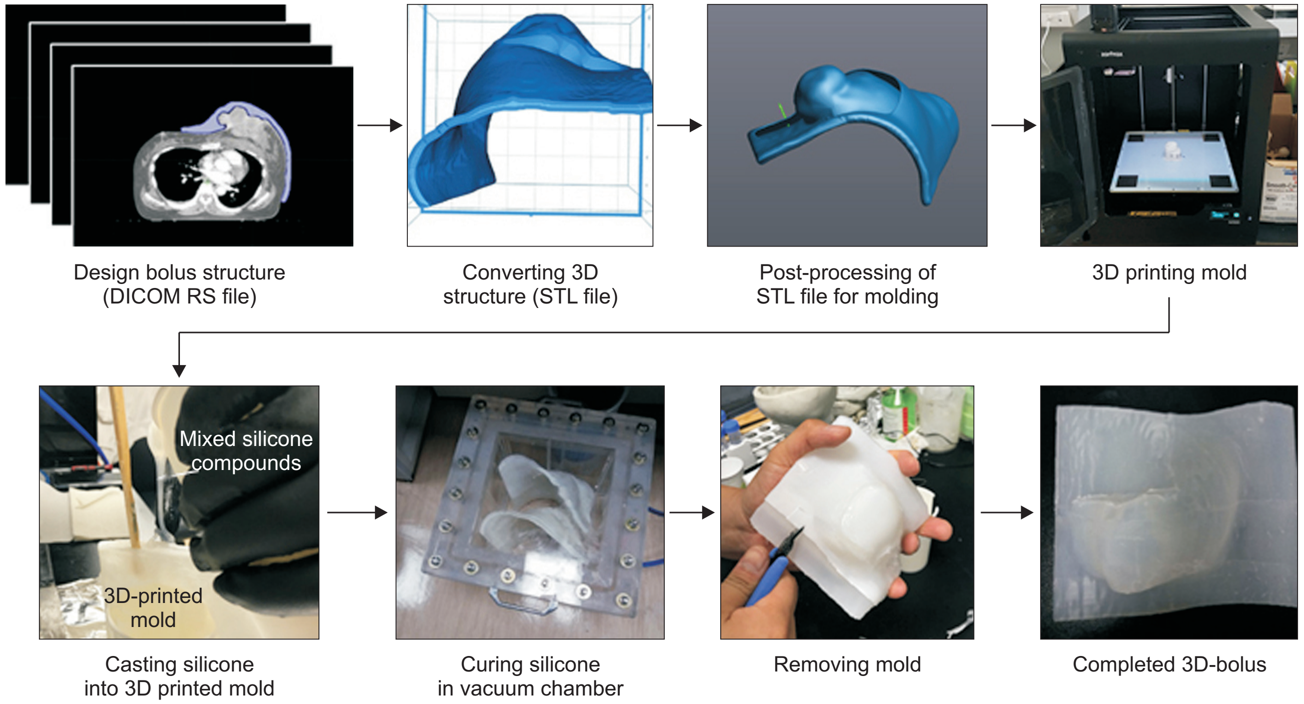


Fig. 1. (a) Transaxial view of patient CT and designed bolus and (b) volume rendering of designed bolus.



Design bolus structure (DICOM RS file) → Converting 3D structure (STL file) → Post-processing of STL file for molding → 3D printing mold → Casting silicone into 3D printed mold → Curing silicone in vacuum chamber → Removing mold → Completed 3D-bolus

Fig. 2. Overall fabrication process of bolus.

Table 1. Physical property of Dragon Skin^{TM} 10 MEDIUM and 3D printer settings.

Physical properties of Dragon Skin^{TM} 10 MEDIUM		Zotrax M300 3D printer setting	
Physical Density	1.179 g/cc	Extruder Temperature	245°C
Electron Density ratio compared to water	1.134	Extrusion Width	0.4 mm
Tensile strength	475 psi	Layer Height	0.14 mm
Tensile Modulus	22 psi	Speed	100 mm/s
Elongation at Break	1000 %	Fill Density	0%
Shore Hardness#	10 A	Fill Type	Mesh
		Fill Angle	30°
		Nozzle Diameter	0.4 mm
		Filament Diameter	1.75 mm
		Layer Thickness	0.14 mm
		Print Quality	High

3. Fabrication of bolus

A summary of the overall bolus fabrication process is shown in Fig. 2. The bolus structure for each patient was the exported DICOM-RT structure format. The segmented bolus structure was converted into an STL file using an open-source software, 3D Slicer (http://www.slicer.org), with a slicer RT module. Instead of direct 3D printing, we casted silicone into 3D printed molds to create a flexible bolus. Post-processing was applied to extend the surface of the bolus structure to a 1-mm thickness and separate the body and lid part for a silicone insertion using VXelements 6.0 (Creaform Inc., Quebec, Canada). The molds were printed on Zotrax 300M (Zotrax, Olsztyn, Poland) with a Z-hips filament. As one of the important printing parameters, the fill density was set to 0%, making it easy to remove the mold from the bolus. In this study, we used harmless silicone on the human skin, known as Dragon Skin^{TM} 10 MEDIUM (Smooth-On, Easton, PA), which has been certified for the safety testing of irritation and skin sensitization. The physical properties of Dragon Skin and 3D printer setting were summarized in Table 1. For casting, the Dragon Skin compounds were mixed and poured into a 3D printed mold. They were then cured at room temperature for approximately 5 h within an in-house vacuum chamber to eliminate air bubbles. As a final step, the mold was removed by cutting from the cured bolus. Fig. 3 shows the produced 3D printed molds and bolus.

4. Geometric analysis

To evaluate the geometrical accuracy, we compared the shapes of the produced bolus with respect to the planned bolus structure from the TPS. The produced bolus was imaged using CT under the same conditions as the patient. Then, the measured bolus image was converted into an STL file for comparison using the mesh information.

The registration process was conducted using Polyworks 2014 software (InnovMetric, Quebec, Canada), which uses the IMAlign module through a cloud-based method for surface matching under the principle of the iterative closest point (ICP) algorithm.[11)] This method iteratively minimizes the distance between the point in one cloud set and its closest point in the other set by estimating the transformation parameters. It allows a comparison of the resulting geometry differences by measuring the average distance between points. We also compared a cross-section profile of the registered bolus geometry and calculated the basic

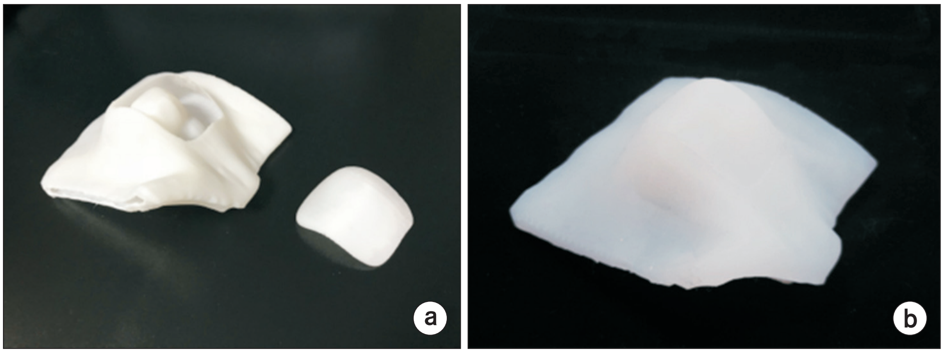


Fig. 3. (a) 3D printed bolus molds with body and lid part, and (b) produced patient-specific bolus.

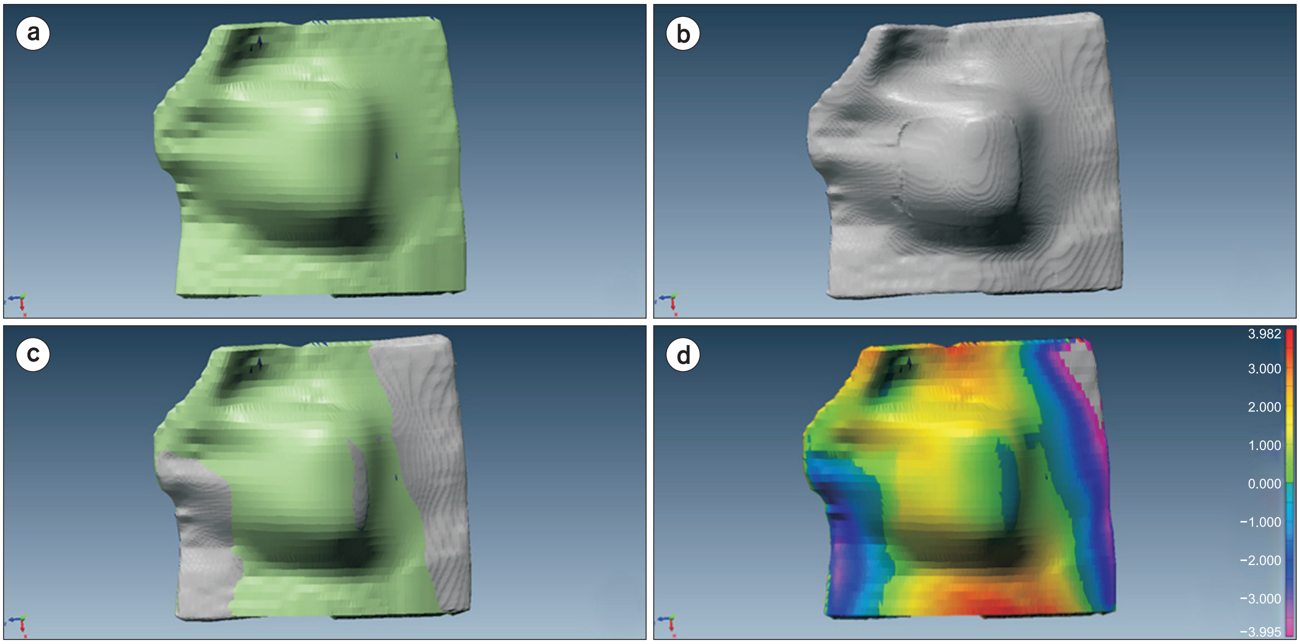


Fig. 4. (a) Planned bolus structure from TPS, (b) measured fabricated bolus structure, (c) superimposed structures after registration, and (d) color map of difference in distance between two structures.

geometric parameter such as the surface area and volume.

Results

1. Average difference in distance

The results of surface-based registration between a planned and measured bolus structure is shown in Fig. 4. The modeling information for each structure is described in Table 2. After iteratively calculating the distance between two points in each cloud as the minimum, the registered meshes were superimposed, as shown in Fig. 4c, and the average distance was visualized as a color map, shown in Fig. 4d. In this calculation, the mean and standard deviation of the difference in distance for each patient are plotted in Fig. 5.

2. Cross-section profile

In each patient case, we compared the geometric difference along the cross-section profile. The geometric values were calculated after dividing five cross-section profiles with equal spacing according to the bolus size. Fig. 6 shows the difference value according to each cross- section profile as a normal vector. Table 3 summarizes the geometric difference value of five cross-sections of each patient.

3. Volume and surface

We also compared the volume and surface area between the planned bolus structure from the TPS and measured the bolus structure from a 3D printed mold and casting

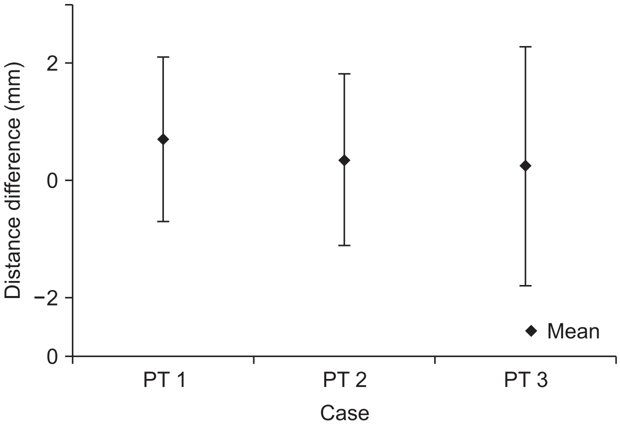


Fig. 6. Equal spacing interval cross-section profile map.

Table 2. 3D modeling information for each structure.

	Patient 1		Patient 2		Patient 3	
	Planned	Fabricated	Planned	Fabricated	Planned	Fabricated
Vertices	62682	30866	29460	40088	163398	194514
Facets	125376	61728	58914	80218	326792	389009

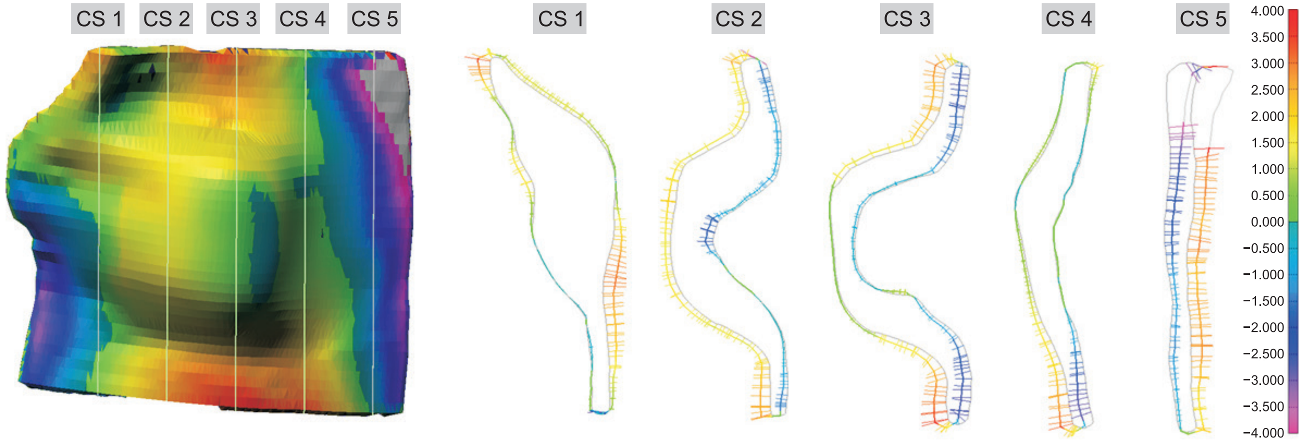


Fig. 5. Difference in distance of registered structure surface.

Table 3. Geometric difference of cross-section profile for each patient.

#	Geometric difference of cross-section profile (mm)					
	Patient 1		Patient 2		Patient 3	
	Mean	STD	Mean	STD	Mean	STD
CS 1	0.82	1.279	0.436	2.209	−0.325	2.237
CS 2	1.076	1.195	0.376	1.166	−0.237	2.044
CS 3	0.721	1.202	0.261	1.572	0.661	1.718
CS 4	0.954	1.645	0.280	1.405	0.369	1.694
CS 5	1.047	1.504	0.743	1.073	−0.055	2.107

STD, standard deviation; CS, cross-section.

Table 4. Comparison of volume and surface between planned and fabricated bolus.

	Patient 1			Patient 2			Patient 3		
	Planned	Fabricated	% diff	Planned	Fabricated	% diff	Planned	Fabricated	% diff
Volume (mm^3)	1026.75	938.73	9.0	125.58	114.27	9.4	2084.63	1971.92	5.6
Area (mm^2)	2048.63	1938.14	5.5	313.65	304.79	2.9	3000.77	2988.07	0.4

bolus. The calculated volume, surface area, and percent of difference are shown in Table 4.

Discussion

In the present study, we introduced a bolus using a 3D printed mold and casting method, and investigated the geometrical accuracy based on the surface registration and basic geometric parameters.

The results of the average difference in distance was within 1 mm, and as the worst case, the absolute difference did not exceed ±2 mm. This discrepancy was negligible in affecting the dose reduction.[3] The results of the cross-section profile showed similar properties with the average difference in distance. According to the cross-section results, CS3, which was the bolus center, had a smaller mean difference than CS1 and CS5, which were the boundary of the bolus. CS3 shows the cross-section near the PTV and is the most important region, providing a dose build-up. The reason for the large difference at the boundary was due to the positional error in the process of CT imaging of the fabricated bolus. This tendency was the most pronounced in a large sized bolus such as the case of patient 3. In addition, one of the limitations of the ICP-based registration is the use of a rigid transformation, which does not consider a non-rigid transformation, increasing the uncertainty of the comparison.

The difference in area between the planned and fabricated bolus structure was less than 5.5%, although the difference in volume was almost 10%. This most likely decreases the volume as the air bubbles are removed during the curing process of the silicone. Therefore, more attention should be paid to the changes in volume during the production process.

Compared to direct 3D printing approach, 3D-printed mold and casting method has several advantages. It is possible to make a bolus using silicone such as Dragon Skin. In addition, various materials can be used to make a bolus suitable for the purpose. It is possible to fabricate a bolus that is more flexible, softer, and less uncomfortable to the patient. It is also easy to make a large-sized bolus through the post-processing of 3D-printed molding. However, there is a disadvantage that labor intensity is required due to mold removal and curing process. The time to make a bolus depends on the output volume, but in general, the direct 3D printing method takes more time for 3D printing to fill the filaments at 100%. The 3D printed mold has only 1-mm thickness and 0% fill density, saving about 30~40% of the time for the 3D printing process.

This study focused on a geometric analysis of a new bolus fabrication. In the future, we will proceed with an investigation into its dosimetric characteristics and clinical application.

Conclusion

As the results show, we determined the feasibility of using a 3D printed mold and casting method for a patient-specific bolus. The geometrical analysis demonstrated that the fabrication of the bolus did not change the shape effect of the dose reduction.

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Conflicts of Interest

The authors have nothing to disclose.

Availability of Data and Materials

All relevant data are within the paper and its Supporting Information files.

Ethics Approval and Consent to Participate

The study was approved by the institutional review board (IRB approval number; 1812-163-999).

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