METHOD

Journal of Anatomy

ANATOMICAL SOCIETY WILEY

A new brain-cutting device and ultraviolet resin-mounted human brain slices as a teaching adjunct for neuroanatomy education

Jin-Yu Lee | Je-Chan Lee | Sung-Young Hong | Eu-Gene Kim | Eun-Jin Lee | Ran-Sook Woo 🆔 | Tai-Kyoung Baik 🆔 | Sang-Pil Oh | Hong-Il Yoo 🆔 | Dae-Yong Song 🆔

Department of Anatomy and Neurosciences, Eulji University School of Medicine, Daejeon, Republic of Korea

Correspondence
Hong-Il Yoo and Dae-Yong Song, Department of Anatomy and Neurosciences, Eulji University School of Medicine, 77 Gyeryong-ro 771beon-gil, Jung-gu, Daejeon 34824, Republic of Korea.
Email: hiyoo@eulji.ac.kr; dysong@eulji.ac.kr

Abstract

Although the level of neuroscience research is rapidly developing with the introduction of new technologies, the method of neuroanatomy education remains at the traditional level and requires improvement to meet the needs of educators and trainees. We developed a new three-dimensional (3D) printed device (human brain-cutting mold, HBCM) for creating human brain slices; moreover, we demonstrated a simple method for creating semi-permanent ultraviolet (UV) resin-mounted brain slice specimens for neuroanatomy education. We obtained brain slices of uniform thickness (3 mm) through the HBCM; the resultant brain slices were optimal for assessing morphological details of the human brain. Furthermore, we used an agar-embedding method for brain-slicing with the HBCM, which minimized geometrical distortions of the brain slices. Also, we prepared semi-permanent brain serial specimens using an acrylic brain slice frame and UV-curable resin, which was highly compatible with moist bio-specimens. During UV resin curing, neither air bubble formation nor color change occurred. The resultant UV resin-mounted brain slices produced definite coronal sections with high transparency and morphological accuracy. We also performed 3D modeling by stacking brain slice images that differentiated the cortical area and nine subcortical regions via manual segmentation. This method could be a reliable alternative for displaying high-quality human brain slices and would be helpful for students and trainee to understand anatomical orientation from 2D images to 3D structures. Also, this may present an innovative approach for preparing and preserving coronal sections of the normal or pathological human brain.

KEYWORDS
cutting mold, education, human brain, neuroanatomy, UV resin

Jin-Yu Lee and Je-Chan Lee contributed equally to this work.

Hong-Il Yoo and Dae-Yong Song contributed equally as the corresponding author.

1 | INTRODUCTION

Human anatomy, including gross anatomy and neuroanatomy, has been considered a key science educational area in undergraduate medical schools (Verhoeven et al., 2002). Traditionally, neuroanatomy education has been carried out using brain specimens (Albanese, 2010); however, significant changes have occurred because of the introduction of new subjects into neuroanatomy curricula as medical scientific knowledge increases (Bergman et al., 2011). The medical education paradigm has also promoted changes from the traditional neuroanatomy teaching strategies to an integrated and clinically oriented curriculum (Papa & Vaccarezza, 2013; Sugand et al., 2010). These changes have reduced the time allocated to neuroanatomy education (Brooks et al., 2015). Therefore, alternative teaching methods in the form of technological innovations, such as three-dimensional (3D) digital applications and/or augmented reality, have been developed and applied in the educational field (Allen et al., 2016; Henssen et al., 2020). A recent review has shown that students prefer new teaching methods because they are considered interactive, engaging, and widely available (Arantes et al., 2018). However, there is a continuous debate on the most appropriate neuroanatomy teaching strategies in undergraduate medical education. Other studies have shown that technology-based teaching methods are not always superior to classic ones (Brenton et al., 2007; Garg et al., 2002). These studies have demonstrated that the ongoing use of human brain specimens is a helpful teaching adjunct to augment students' knowledge of neuroanatomy.

The most traditional method used for a course on brain cross-sectional anatomy is the arbitrary manual cutting (using a brain knife) and display of formalin-fixed brain slices. The disadvantage of this method is that the thickness of the brain slices is not constant. If too thin, the brain slices are difficult to handle and can damage easily due to careless manipulation; if too thick, students might not observe some important anatomical structures in each slice (Opeskin & Anderson, 1994). Other alternative neuroanatomy teaching methods involve the use of color atlases and plastic models of the human brain, but these lack accuracy and realistic features of human brain specimens (Hwang et al., 2006). Therefore, the first condition for brain slices to overcome existing constraints is that the serial brain sections should be thin and evenly spaced.

For the purpose of cutting thin and evenly, the brain should be embedded in an appropriate medium to arrange and fix it in a desired configuration or orientation. Agar is the classical medium used for embedding the brain (Ghassemifar & Franzen, 1992). Molten agar is poured over the tissues in an appropriate container (mold); the agar solidifies and fixes the brain tissues in a desired shape and orientation. Gelatin is another embedding medium; however, the tissue fixing process is more difficult because gelatin is harder and stickier than agar (Jones & Calabresi, 2007). Agar has other advantages as an embedding medium: (i) easy and rapid conversion from liquid to solid state and vice versa through temperature changes; (ii) relative cost-effectiveness. Other media routinely used for embedding samples in histology and electron microscopy include paraffin and various plastics (polyester, Plexiglas, polyacrylamide, Epon 812, etc.). Paraffin embedding is relatively simple and inexpensive, whereas plastic embedding is considered more challenging and expensive (Kurth et al., 2012).

The second condition for brain slices to overcome existing constraints is to semi-permanently preserve brain slice specimens. Many studies have been conducted to achieve semi-permanent tissue preservation; over the last 20 years, plastination has been one of the most popular techniques for the long-term preservation of a dissected human body (Fruhstorfer et al., 2011; Latorre et al., 2007). However, it also has some limitations. This process is quite time-consuming, and a considerable level of skilled manpower is required. Plastination laboratory development also requires a substantial expense (Bin et al., 2016). Additionally, there are health and safety concerns as significant amounts of flammable chemicals are produced as byproducts in the preparation of plastinated specimens (Estai & Bunt, 2016). These limitations have led to the development of simpler and more cost-effective methods of long-term specimen preservation than plastination.

Polymer resins, such as silicon rubber, epoxy, or polyester have common properties: They start as a clear sticky fluid and then harden permanently to form a thick and glossy coating when exposed to open air for a certain period of time. Usually, a liquid catalyst is used to shorten the hardening (curing) time of a liquid polymer resin. However, there are serious limitations in the use of these resins as tools for the semi-permanent coating of bio-specimens. It is normal for the resin to heat up during the resin curing process because of the chemical reactions that occur between the resin and catalyst. During curing, moist bio-specimen may also create air bubbles, which makes lower the transparency of the resin and clarity of specimen. The ultimate problem is that the polymer resin does not have an affinity for moisture; therefore, dehydration and substitution processes are a prerequisite for resin mounting (Gao et al., 2006). Ultraviolet (UV)-curing resins are a practical alternative to conventional polymer resins. They polymerize and cure in a short time via the energy of UV light without the use of other catalysts, and are highly compatible with moisture (De Kok et al., 2015; Jongsma et al., 2012).

In this study, we had two aims: (1) to provide a comprehensive and reproducible description of new methods involved in the process of developing a new device that can be used to cut the human brain in uniform intervals and thickness; and (2) to describe the process of developing UV resin-mounted semi-permanent brain specimens and 3D reconstruction of segmented brain images that can subsequently be employed as neuroscience teaching resources.

2 | MATERIALS AND METHODS

2.1 | Scheme of the study

The scheme of this study is illustrated in Figure 1. To attain the first aim, we designed a new human brain-cutting mold (HBCM) that can be used to guide the cutting of human brains at regular
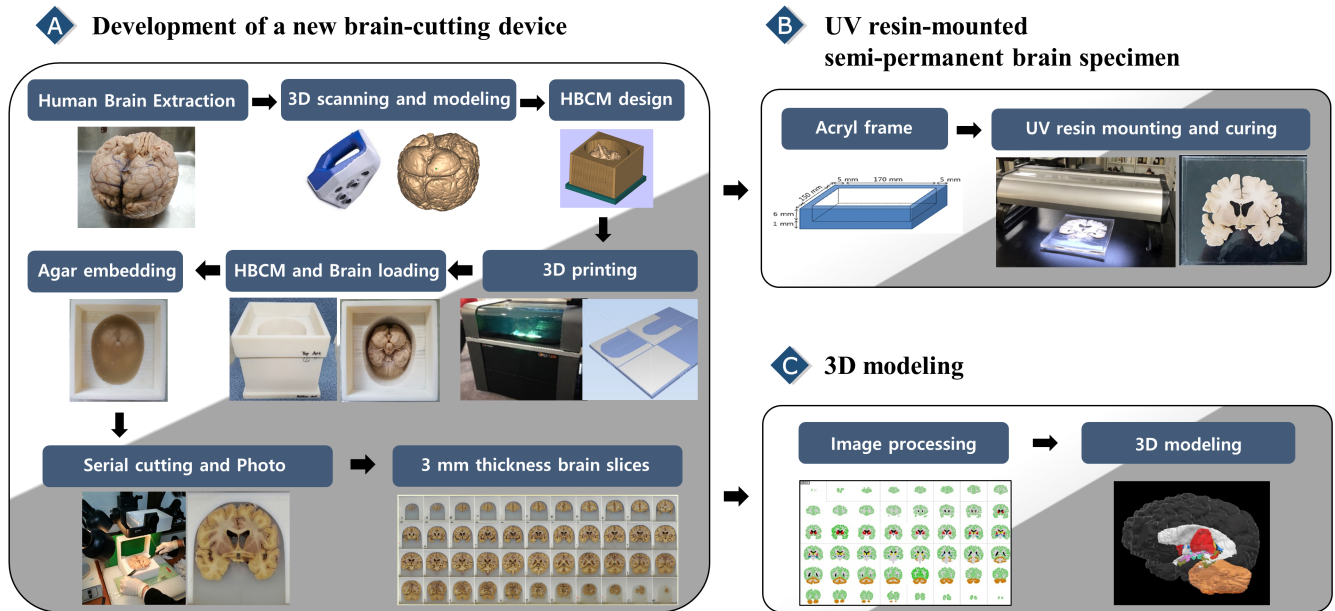
A **Development of a new brain-cutting device**

B **UV resin-mounted semi-permanent brain specimen**

C **3D modeling**

FIGURE 1 Scheme of study design. 3D, three-dimensional; HBCM, human brain-cutting mold; UV, ultraviolet.
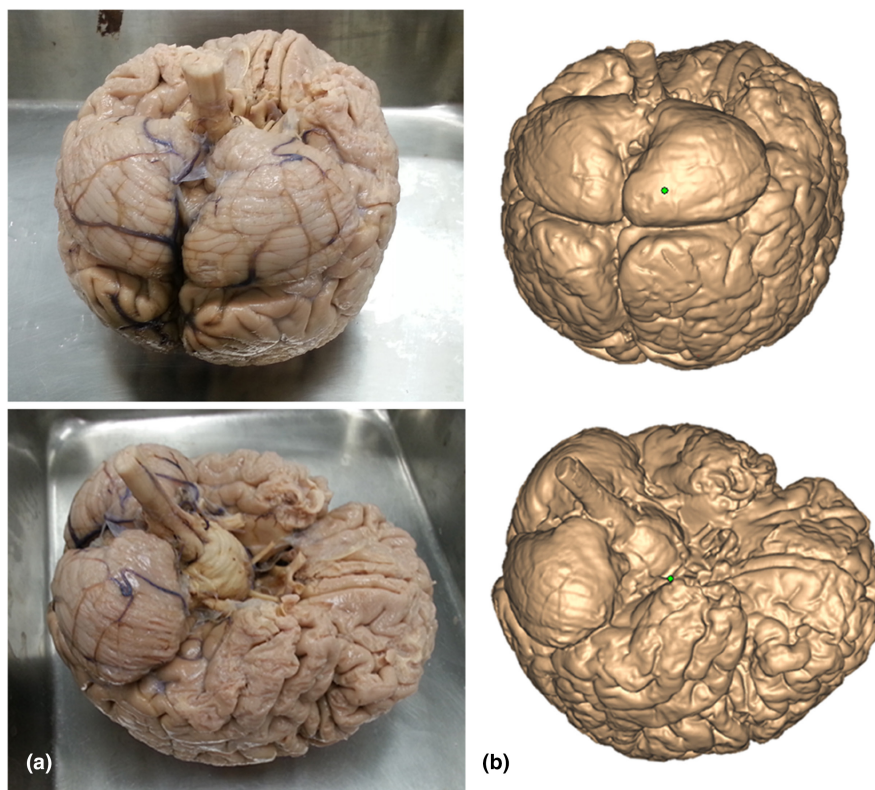

FIGURE 2 The brain of a 78-year-old female cadaver (a). Three-dimensional image of the brain obtained using a portable three-dimensional scanner (b).

intervals. To attain the second aim, we assessed various types of commercially available resins used to make semi-permanent brain slices and selected the best option. Furthermore, we created a visible 3D brain model by stacking acquired serial brain images.

2.2 | Human brain

Brains were obtained from cadavers donated to our institution (Eulji University School of Medicine) within 72 h post-mortem. Each donor had provided prior written comprehensive consent, which includes

permission—granted by the donor at the time of registration and documented in a declaration form—to retain parts of the body for further education and research purposes.

Cadavers were embalmed through the femoral artery with embalming fluid (35% formaldehyde solution, 1.5 L; 95% ethanol, 4.0 L; 99% glycerol, 1.5 L; and water, 8.0 L). Six to ten months after embalming, cadavers were removed from storage, and the brains were extracted according to the conventional dissection method (Morton et al., 2004). Briefly, the scalp of the cadaver was stripped from the skull, and the calvaria was cut using an oscillating saw. After removing the dura mater, the internal carotid arteries and cranial nerves were carefully incised at the internal surface of the cranial base. The border of the brain and spinal cord was cut at the foramen magnum. After extraction, the brains were stored in 10% phosphate-buffered formalin solution (35% formaldehyde solution, 100 ml; water, 900 ml; sodium phosphate monobasic, 4.0 g; and sodium phosphate dibasic [anhydrous], 6.5 g) at room temperature. Five brains were used in this study, of which four were not completed to the final form due to the trial of earlier versions of the HBCM; therefore, we presented our findings using the brain of a 78-year-old female cadaver (Figure 2a).

2.3 | The HBCM

We developed an HBCM for obtaining serial coronal brain slices with a uniform thickness of 3 mm. Three-dimensional images of the brain surface were obtained using a portable 3D scanner (Artec Space Spider; Artec 3D Co., Rue Jean Engling, Luxembourg) (Figure 2b), and the HBCM was designed based on the 3D brain surface image obtained from the 3D scanner (Figures 3–5). The HBCM was then created using a 3D printer (Objet500 CONNEX3, Stratasys Co., Eden Prairie, MN, USA). The Korea Institute of Industrial Technology (Ansan Research Center) assisted in 3D image scanning and 3D printing.

The printed HBCM was composed of three parts; the cover, bottom, and body (Figure 3). The cover was 210.000 mm wide, 210.000 mm long, and 49.894 mm high (Figure 3a). The bottom was 220.000 mm wide, 220.000 mm long, and 20.000 mm high

(Figure 3b). The body was 200.000 mm wide, 200.000 mm long, and 154.566 mm high (Figure 3c). The body was composed of 56 plates, and the thickness of the 2nd to 55th plates was 3 mm each (Figure 4). The plates at both ends (the 1st and 56th plates) were 10.0 mm thick such that the HBCM could be stable when set up (Figure 4). The cover and bottom included gaps (3 mm) in which each plate of the body could be inserted and fixed, with an interval between adjacent gaps measuring 0.3 mm (Figure 4). Figure 5 represents the lateral (Figure 5a,b), superior (Figure 5c), and superolateral (Figure 5d) views of the HBCM design. The internal pocket of the HBCM, where the brain was placed, needed more space to load the brain and align it to the desired location. To this end, it was designed to create an extra space of approximately 15 mm for fingers to enter the frontal and occipital poles of the brain (Figure 5b). Approximately 10 mm extra spaces were also created at both sides of the temporal lobes. Therefore, although there may be some differences depending on the size of the brain, the HBCM was designed to reuse for almost any size of the brain and that will facilitate the creation of brain slices with consistent thickness. VeroWhite (Stratasys Co.) was used as the 3D printing material, considering the durability, and deformation plasticity of the HBCM. The assembly process of the HBCM is shown in Figure 6.

2.4 | Coronal brain section

The brain was loaded in the HBCM, such that the ventral surface of the brain was oriented upward, and the frontal and occipital poles of the brain were in the same horizontal plane (Figure 7a,b). A 2% agar solution was prepared by heating and magnetic stirring. Preliminary experiments showed that a 2% agar solution was the best suitable concentration for brain embedding than 0.5%, 1%, 3%, 4%, and 5% agar solutions. The solution was cooled to 70°C and poured into the HBCM to completely cover the whole brain. To prevent agar leakage, the body and bottom of the HBCM were completely covered with plastic vinyl. The agar solution was allowed to cool to room temperature overnight (Figure 7c,d).
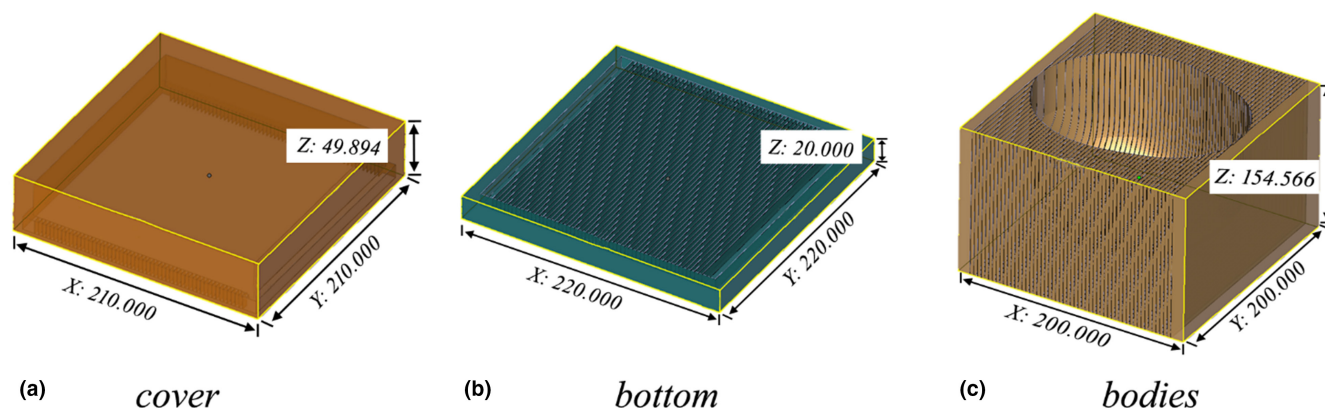

(a) cover Z: 49.894 X: 210.000 Y: 210.000

(b) bottom Z: 20.000 X: 220.000 Y: 220.000

(c) bodies Z: 154.566 X: 200.000 Y: 200.000

FIGURE 3 Composition and design of the HBCM. The HBCM is composed of a cover, bottom, and body with plates. (a–c) show the superior oblique views of the cover (a), bottom (b), and plates of the body (c).
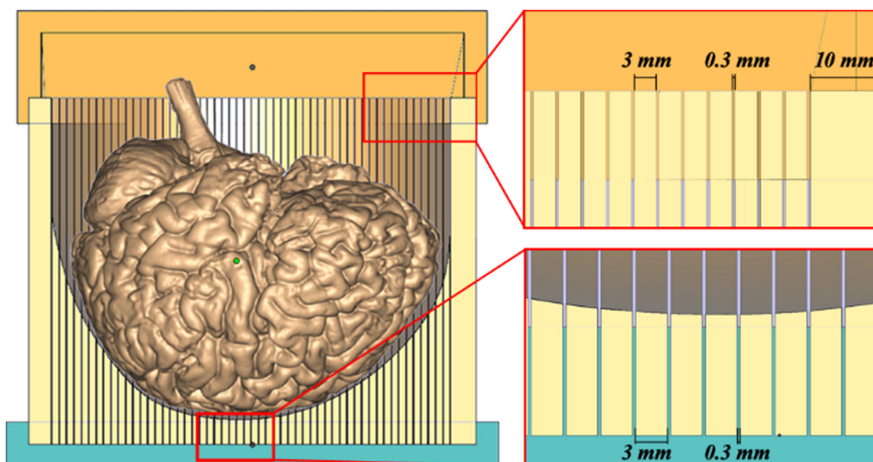
FIGURE 4 Lateral aspect of the HBCM design drawing. The enlarged square box image represents the thickness of each plate of the HBCM body and the width of the gaps. The thickness of the 2nd to 55th plates of the body is 3 mm each and that of each ending plate (1st and 56th plates) is 10.0 mm. Moreover, 0.3-mm gaps (slits) were made between each plate.
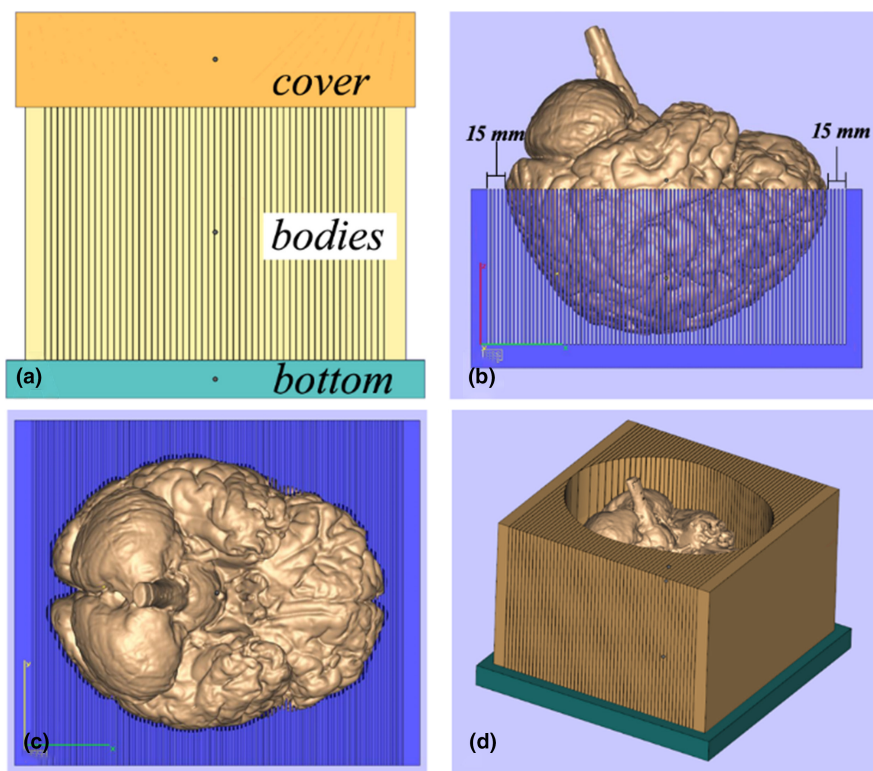

FIGURE 5 Representative drawing of the HBCM (a) when the brain is loaded (b–d). The internal pocket of the HBCM has an extra space of about 15 mm for adjusting the brain to the desired location (b).

After agar-embedding was completed, the HBCM was rotated, such that the plates of the HBCM body were parallel to the floor (Figure 8a). After removing the bottom from the body, brain-coronal sections were prepared at intervals of 3 mm using a brain knife (Tissue-Tek® Accu-Edge® 4790 Trimming Knife Handle, Long, SAKURA). Manual brain cutting was performed by serially removing the plates of the HBCM body, starting from the uppermost plate (Figure 8b). Starting from the direction of the frontal pole of the brain, a total of 48 slices were obtained from the 5th and 52nd plates of the HBCM body, respectively. Each slice was sequentially stored in a 10% phosphate-buffered formalin solution until use.

2.5 | Photos, image processing, and 3D modeling

The ability to reconstruct two-dimensional (2D) serial sections into a 3D whole structure is important for students or trainees to obtain precise anatomical knowledge of the human brain. Therefore, based
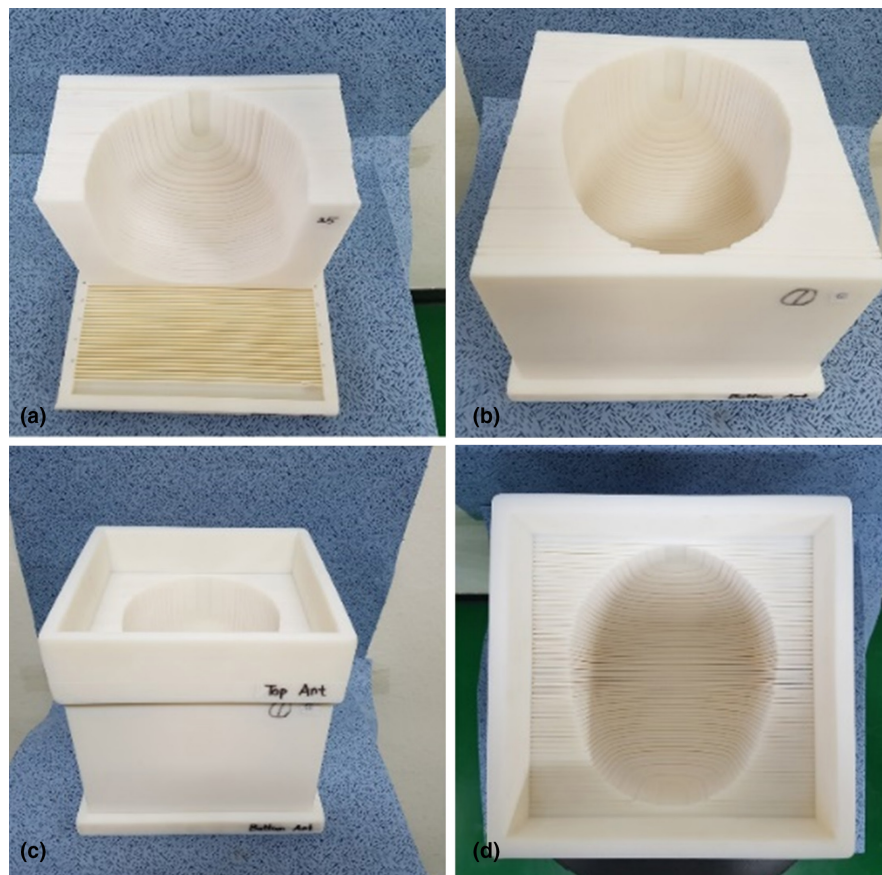
FIGURE 6 The assembly process of the HBCM. Anterosuperior view of the HBCM showing half (a) and all of the plates (b) assembled on the bottom. The anterosuperior (c) and superior (d) views of a completely assembled HBCM.

on the 2D images of serial brain sections generated during brain cutting, 3D modeling of the brain surface and the main subcortical structures of the brain was performed.

Photographs of each coronal section of the brain were obtained at a uniform distance of 19.9 cm between the camera lens and each brain slice surface using a Samsung Galaxy S7 camera (Samsung Co.) and Kaiser Copy Stand RS1 with RA-1 Arm (Kaiser Fototechnik GmbH & Co. KG), followed by removing the uppermost plate and cutting the exposed brain serially (Figure 8b,c).

To confirm whether the main anatomical structures in the coronal section of the brain could be distinguished from each other, a brain map was created at the level of the anterior commissure (Figure 8d). We differentiated and delineated 31 major brain areas (Haines & Mihailoff, 2018): longitudinal fissure and six sulci (cingulate, superior frontal, inferior frontal, lateral, superior temporal, and collateral sulci), eight gyri (cingulate, superior frontal, medial frontal, inferior frontal, superior temporal, middle frontal, occipitotemporal, and parahippocampal gyri), seven white matter (corpus callosum, internal capsule, external capsule, extreme capsule, external medullary lamina, anterior commissure, and optic chiasm), six subcortical nuclei (caudate nucleus, globus pallidus, putamen, claustrum, amygdala, and substantia innominata), and three other structures (septum pellucidum, lateral ventricle, and insula). Figure 8e shows 44 serial brain sectional images (four extreme end images of the frontal and

occipital poles are omitted, as they did not have significant anatomical structures) obtained in this study.

For 3D modeling, each brain slice image was imported into Adobe Photoshop (version 7.0; Adobe Systems Inc.) and the unnecessary background including agar was removed manually, defining the outline of the brain. Subsequently, the cortical area and nine subcortical regions (lateral ventricle, 3rd ventricle, basal nuclei, cerebellum, hippocampus, optic tract, fornix, thalamus, and substantia nigra) in each slice image were outlined to create segmented images (Figure 9a). After converting each retained image to JPEG format, a 3D brain model was reconstructed by stacking the 2D images using 3D-DOCTOR (Able Software Co.) (Figure 9b and Video S1).

2.6 | UV resin mounting on a transparent acryl resin frame

Before UV resin mounting, excess agar was trimmed away from the brain surface, and the agar present in the ventricles was manually removed. However, in this trimming process, the agar interconnecting parts of the brain in the coronal sections (for example, agar between the temporal pole of the cerebrum and cerebellum) were not removed. This could minimize the geometrical distortions of the
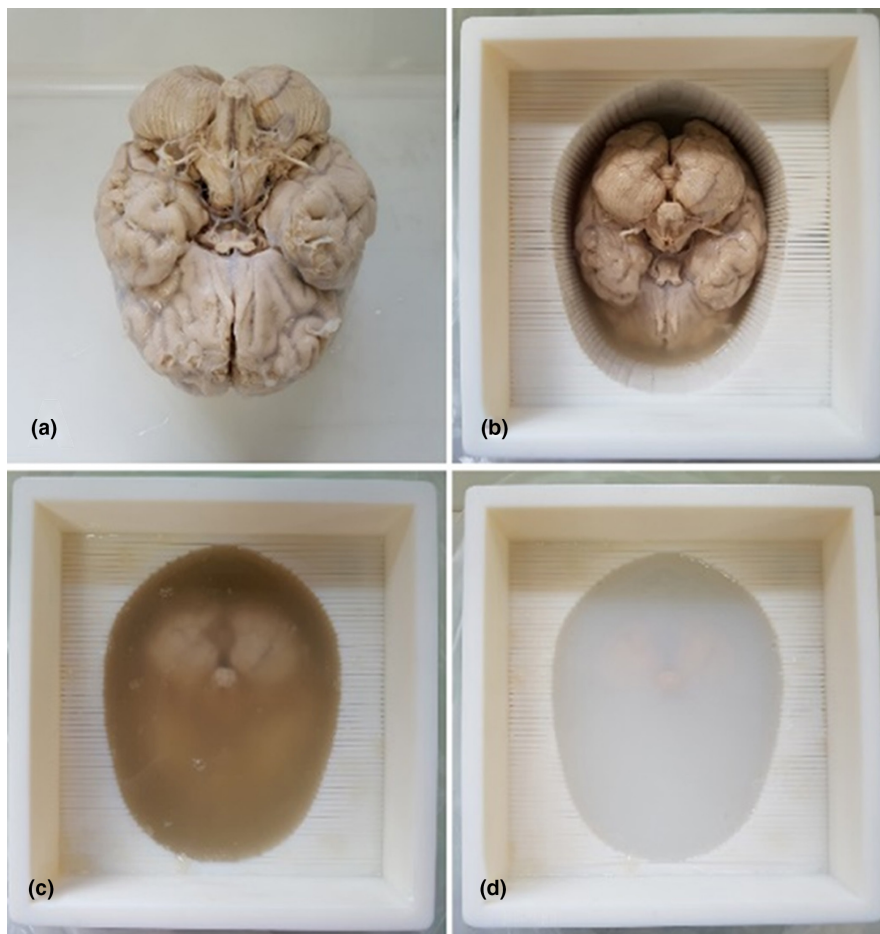
FIGURE 7 The agar-embedding procedure. The brain is placed in the HBCM (a, b) and a 2% agar solution is poured into the HBCM to completely cover the brain (c); the agar is completely solidified (d).

brain slices because the agar interconnecting the brain parts makes them lie in their original position.

A frame capable of containing a brain slice was prepared using acrylic resin (Figure 10a). The brain slice frame was large enough to contain the largest brain slice; 180.0, 160.0, and 7.0 mm in width, length, and height, respectively, with a 5.0 mm thickness in width and length, and a 1.0 mm thickness at the bottom. A sheet of each brain slice image with a true scale was placed under each frame to aid in the placement of the brain slices in the same anatomical position.

UV resin-mounted coronal brain slices were made using an acryl brain slice frame and UV-curable resin (UV Resin Hard Type, Padico). In this study, we considered and tested three types of synthetic resins during preliminary experiments: polyester, polyurethane, and UV curable resins. Polyester and polyurethane resins showed low transparency, and tissue damages (shrinkage, deformation, and color changes) occurred due to the exothermal process during hardening. Specifically, during the process of resin hardening, numerous air bubbles appeared, and the resin turned blurry. The air bubble formation and the blurriness seemed to be caused by the immiscibility of synthetic resins with moisture contained in the bio-specimen (Gibbons, 1959).

Approximately 10 ml of UV resin was applied to the bottom of the prepared acryl brain slice frame, and the resin was polymerized by irradiating 265 nm UV light for approximately 5 min. The brain slice was dried briefly by placing and gently pressing several sheets of paper towels above and below the brain slices for 1–2 min. Subsequently, the dried brain slice was carefully placed into the frame on the top of the hardened resin, and a UV resin solution was poured until the resin covered approximately half (1.5 mm) of the brain slice. The amount of resin required varied depending on the size of each brain slice. Thereafter, the UV light was irradiated briefly to fix the brain slice in the desired position, after which the UV resin solution was added until it completely covered the remaining brain slice. The height of the resin was approximately matched with the height of the brain slice frame. At this point, any visible air bubbles were removed by either piercing them with a probe or moving them to the edge of the acryl brain slice frame. The final polymerization reaction was conducted by irradiating UV light for 15–20 min (Figure 10b). The interface between each resin layer was almost imperceptible. Figure 10c shows a representative image of the semi-permanent UV resin-mounted coronal brain slice at the level of the optic chiasm plane. Figure 10d shows the 38 semi-permanent UV resin-mounted brain slices; among a total of 48 brain slices obtained, 10 extreme ends of the frontal and occipital pole slices were excluded because they did not contain any significant anatomical structures.
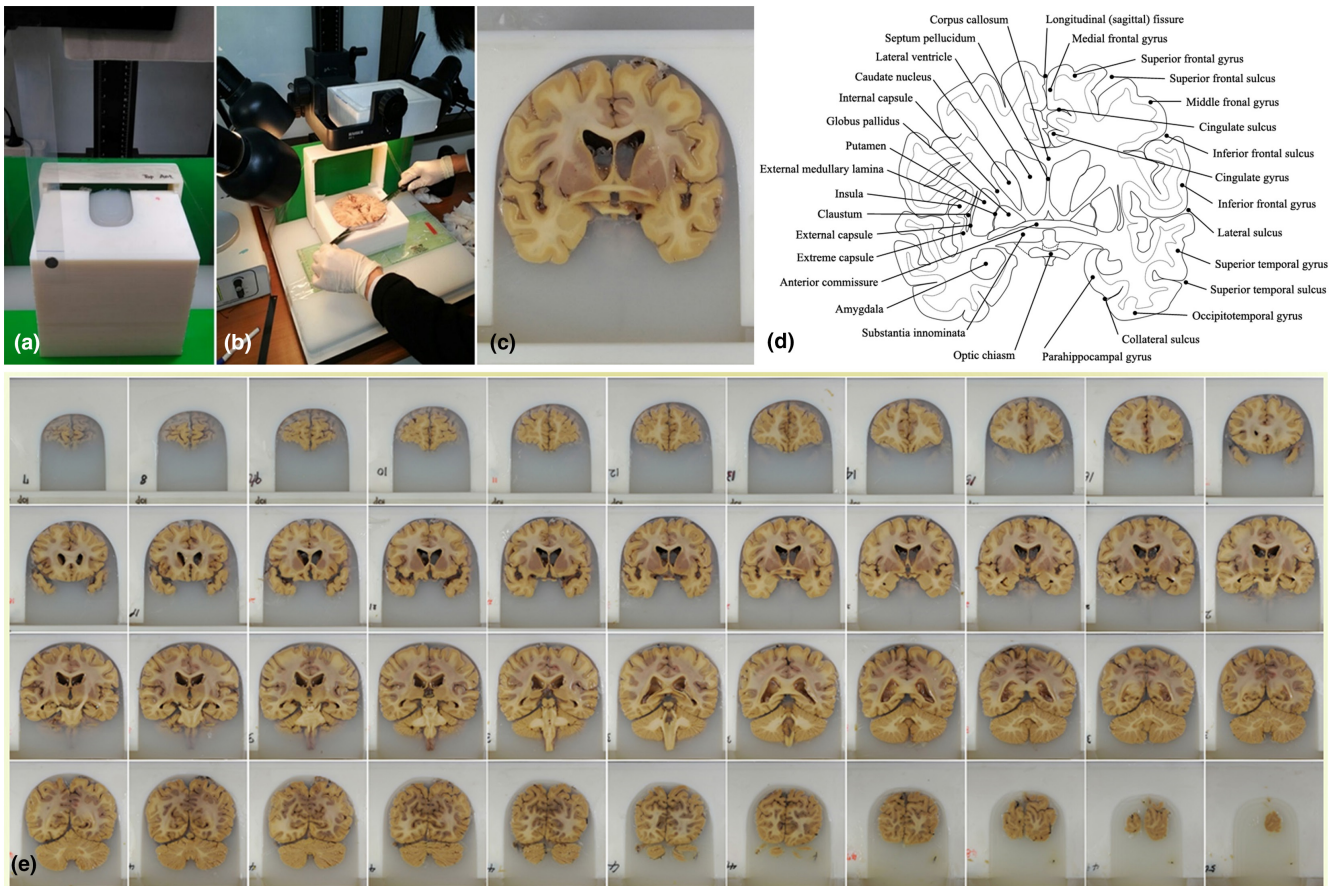
FIGURE 8 The brain-cutting process. The HBCM is rotated in a direction perpendicular to the floor and the bottom is removed from the body (a). Fabrication of a brain-coronal slice using a brain knife (b). Agar-embedded coronal brain section at the level of the anterior commissural plane (c). A brain map of the coronal brain section at the level of the anterior commissural plane (d). Forty-four serial brain sectional images were obtained in this study (e).
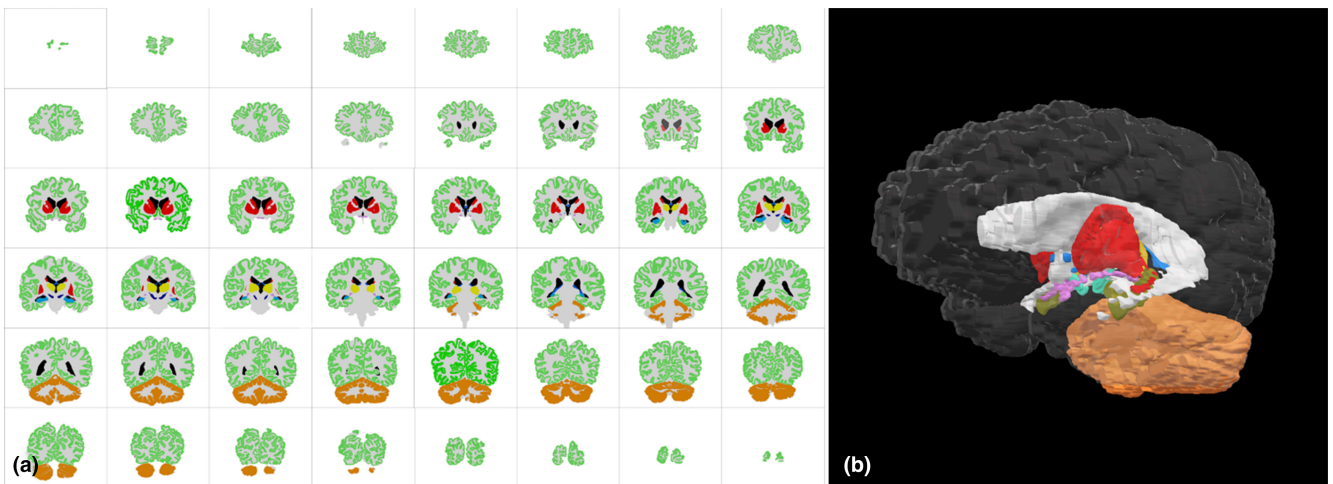

FIGURE 9 Segmentation and 3D modeling of the human brain. Based on photographs of 48 serial coronal brain slices, the cortical area (green in a and light gray in b) and nine subcortical regions are segmented, and a 3D brain model is reconstructed. The nine subcortical areas are as follows: Lateral ventricle and 3rd ventricle (black in a and white in b), basal nuclei (red in a and b), cerebellum (orange in a and b), hippocampus (sky blue in a and mustard green in b), optic tract (pink in a and b), fornix (blue in a and b), thalamus (yellow in a and b), and substantia nigra (indigo blue in a and sky blue in b).
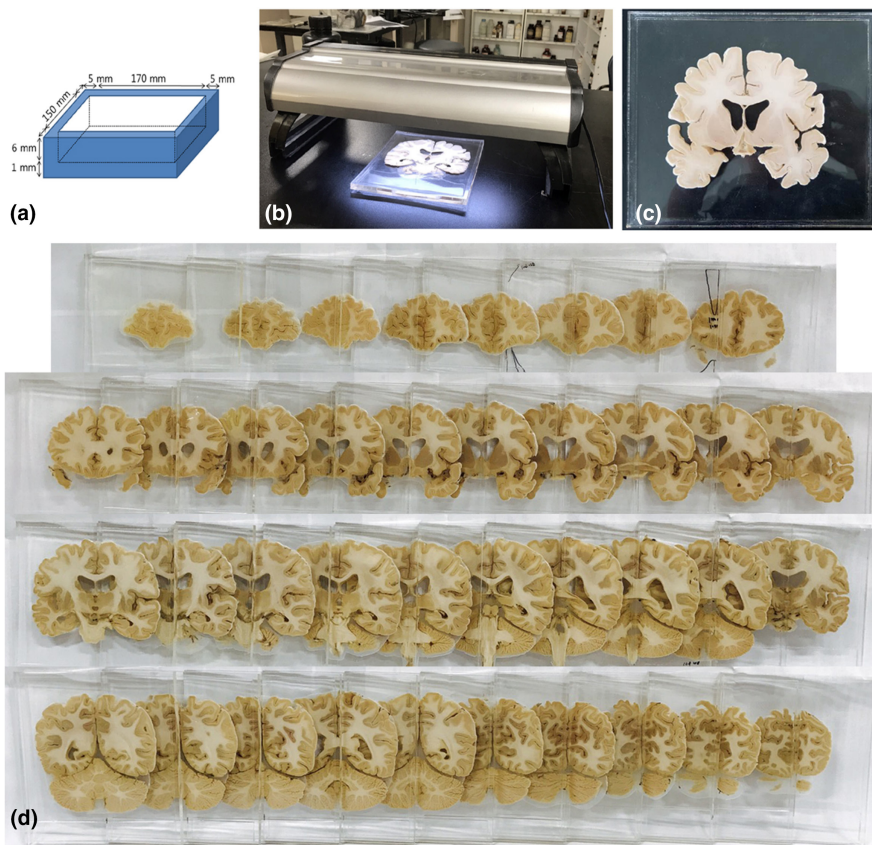
FIGURE 10 The process of making semi-permanent ultraviolet (UV) resin-mounted coronal brain slices. Design diagram for acryl brain slice frame (180.0, 160.0, and 7.0 mm in width, length, and height, respectively, with a 5.0 mm thickness in width and length, and a 1.0 mm thickness at the bottom) (a). The UV resin curing process involving an irradiation with 265 nm UV light (b). A semi-permanent UV resin-mounted coronal brain slice at the level of optic chiasm plane (c). Complete whole semi-permanent UV resin-mounted serial brain slices (d).

3 | RESULTS AND DISCUSSION

3.1 | The HBCM

Several researchers have developed and presented devices that can be used to cut the human brain at uniform intervals (Opeskin & Anderson, 1994; Zarow et al., 2004). However, their methods were not appropriate for providing continuous whole-brain slices at regular intervals. In the method described by Opeskin and Anderson, there was no significant difference from manual brain cutting, except that brain cutting was performed using a guide frame with a certain thickness (Opeskin & Anderson, 1994). Manual brain cutting results in an inevitable loss of proper anatomical positions, as anatomical structures may fall off from each other in each brain slice. In the method described by Zarow, the thicknesses of brain slices were not constant, and the resultant slices were too thick (1–2 cm) (Zarow et al., 2004). Therefore, we developed a new brain-cutting device (HBCM) that can cut the whole brain serially with a 3-mm thickness, as cross-sectional magnetic resonance and computed tomographic images are usually provided at intervals of 3 or 5 mm.

Based on the 3D brain surface image obtained using the portable 3D scanner, the cover, bottom, and 56 plates of the body of the HBCM were designed (Figures 2–5). The HBCM parts were manufactured using 3D printing, and 56 plates of the HBCM body were assembled to the HBCM bottom and cover; hence, HBCM stability was obtained (Figure 6).

During the development of the HBCM, we encountered and overcame some challenges. Initially, we intended to produce the HBCM using the same design as the rodent brain mold, which is commercially available for use in the neuroscience research field. However, it was deemed impossible to produce the HBCM using an all-in-one design such as that of a rodent brain mold, as each plate of the HBCM body was very thin (3 mm); thus, a plate could not maintain a straight stable shape without bending. Therefore, the HBCM was fabricated as an assembly-type mold.

3.2 | Agar-embedding and brain sectioning

We employed an agar-embedding method for brain cutting; this method was simple and more effective than other methods such as using a polycut after celloidin-embedding (Challa et al., 2002) or a cryomacrotome after freezing (Toga et al., 1994). Agar provides a semi-rigid matrix that minimizes the geometrical distortions that may arise from hand cutting. Furthermore, parts of the brain that

may be lost or displaced during hand-cutting could retain their proper anatomical positions and relations, as the agar links several brain parts (Zarow et al., 2004). For example, the temporal poles of the cerebrum and cerebellum, which would normally fall free from each brain slice during hand-cutting, maintained a stable anatomical relationship with other brain regions. Through these processes, we succeeded in making consecutive human brain coronal slices of uniform thickness (3 mm).

After assembling the HBCM, we encountered a challenge in the brain cutting process. The first attempt to create consecutive coronal brain slices was performed by placing 48 brain knives at knife slits (0.3-mm gaps between each adjacent plate of HBCM, Figure 4) followed by cutting the whole brain simultaneously from top to bottom. However, the resistance formed between the brain knives and the knife slits, and between the brain knives and the brain parenchyma, made it impossible to cut the whole brain simultaneously. To overcome this challenge, the HBCM was rotated in a direction perpendicular to the cover and bottom of the HBCM, such that the plates of the body were placed parallel to the floor. Subsequently, each slice of the brain was cut separately after removing the plates of the body one by one. Notably, 3D printing technology is based on the additive manufacturing process, and one of the disadvantages of this technology is poor surface quality. Although the surface quality varies depending on the layer height, wall thickness, printing speed, and temperature, the surface roughness values for fused deposition modeling processes ranged between 2.46 and 40 μm (Akande, 2015; Campbell et al., 2002). The surface roughness makes the resistance to the smooth sliding of the brain knife on the HBCM plate surface. Therefore, we polished both surfaces of each plate of the body using fine sandpaper to minimize the surface roughness of the HBCM.

3.3 | UV resin-mounted brain slice in a transparent acryl resin frame

The completed UV resin-mounted brain slices showed high transparency, which was similar to that observed with the naked eye without the resin (Figure 10c). No distortion of brain tissue was observed during the hardening of the UV resin (Figure 10d). UV curing resin is widely used in dental restoration and prosthodontic treatment because of its properties, such as rapid curing time, a variety of color choices, and durability after curing (De Kok et al., 2015; Jongsma et al., 2012). Considering these characteristics of UV resin, it was possibly the most suitable resin for producing semi-permanent, moist brain slices. The resultant UV resin-mounted brain slices have shown satisfactory quality for neuroscience education. As long as they are handled with care during observation, they maintain their integrity and quality.

The plastination technique, first developed by Gunther von Hagens (von Hagens et al., 1987), has become one of the most favorable methods for the long-term preservation of the human body because it is odorless, conveniently stored, and easily handled (Fruhstorfer et al., 2011; Jones & Whitaker, 2009). However, it is difficult to regard plastination as a realistic and/or accurate brain specimen preservation method because it requires multi-step pretreatment processes. For plastination to be effective, moist brain slices should be dehydrated, fat eliminated, and brain parenchyma substituted with plastic using vacuum-forced tissue impregnation (Bin et al., 2016; Sora et al., 2019). The dehydration and fat elimination processes inevitably involve severe tissue shrinkage, and the impregnation process changes the color of brain tissue. This makes the gray and white matter of the brain tissue somewhat indistinguishable, which obscures anatomical details, thereby necessitating additional staining methods such as Prussian blue impregnation (Riederer, 2014). Moreover, plastination is expensive in terms of equipment and reagents, and time-consuming. Therefore, we employed UV resin as a mounting material to prepare semi-permanent specimens with satisfactory quality for education.

The manipulation of UV resin-mounted brain slices by students and teachers is not harmful, as the chemical ingredients of UV resin react to form a non-hazardous solid. However, the curing reaction is somewhat exothermic and produces noxious fumes, and thus the curing process should be conducted in a well-ventilated laboratory; moreover, the implementer should wear gas masks and protective goggles.

3.4 | 3D modeling

We performed 3D modeling based on the consecutive segmented coronal brain images acquired (Figure 9a). The completed 3D brain model represented the 3D location and connectivity of each segmented region (Figure 9b and Video S1).

In recent studies, 3D reconstruction models of the human brain have been used as teaching tools in neuroanatomy classes (Arantes et al., 2018). Previous studies have shown that a 3D computer graphical demonstration of the spatial relations between 2D sectional anatomy and 3D whole anatomy leads to integrative learning, an increase in student performance, and a high long-term retention of brain anatomy (Naaz et al., 2014; Pani et al., 2013). Therefore, the use of 3D computer graphic programs is advantageous in neuroanatomy education. However, these graphic programs are standardized models, which may be disadvantageous when used to examine the actual diversity of the human brain. Our study suggests that students can easily implement relatively specific 3D brain graphics based on 2D serial cross-sectional images of human brains provided in a neuroanatomy laboratory class. For example, if an outline of each cross-section is provided, a 3D structural relationship between the hippocampus and fornix in the brain can be demonstrated in about 5–10 min. Therefore, these educational activities can help students increase their participation in education, improve their understanding, and recognize the diversity of the human brain through comparison with other brain images provided in a neuroanatomy class.

4 | STRENGTHS AND LIMITATIONS OF THE STUDY

One of the strengths of this study is that our methods can be easily and quickly applied. It took 1 day for agar-embedding, 2–3 h for brain cutting and photo, and approximately 20 min for UV resin mounting in each brain slices. Moreover, our methods are cost-effective. The average cost of producing one UV resin-mounted brain slice was approximately USD 30 (cassette, USD 5; and UV resin, USD 25). In addition, our methods do not require specialized equipment (vacuum chamber, acetone baths) or intensive labor, unlike plastination and other previously proposed resin models (Bin et al., 2016; Chisholm & Varsou, 2018). In clinical settings, the method we developed will help preserve specific pathological cases. If the unusual and important clinical cases are preserved and accumulated as semi-permanent specimens, it will be valuable for education and research in translational neuroscience. The greatest strength of our proposed method is that it provides a real brain. Our method does not require dehydration and degreasing processes, which inevitably result in deformation and discoloration of tissue samples.

One limitation of this study is that we did not provide a method of maintaining the shape and color of UV-mounted brain specimens for a longer time. Three to 4 years after specimen production, the brain slices undergo color changes and fine shrinkage, which is presumably caused by evaporation through the fine holes of the plastic frame and UV resin. Therefore, any treatment that can prevent water evaporation, for example, waterproof coating, could be helpful in preserving the specimens. Another consideration is that the HBCM, which was made from 3D printing, should be remade using durable metallic materials because it has a tendency to become photodegradable and less durable after a long time.

5 | CONCLUSIONS

We developed a new HBCM that provides brain slices of uniform thickness (3 mm) optimal for assessing morphological details of the brain. Furthermore, we produced semi-permanent coronal human brain slice specimens using UV resin. The anatomical details, including the colors of the white and gray matter of the brain and the position of the brain parts, were well preserved, such that the slices provided real images for neuroanatomy education. UV resin-mounted brain slices can be safely manipulated by students and teachers, thereby enhancing students' opportunities for visual examination. Moreover, 3D modeling based on 2D images of serial brain sections may also increase student participation in education and improve their understanding.

AUTHOR CONTRIBUTIONS

JYL and JCL: concept/design, acquisition of data, data analysis/interpretation, drafting of the manuscript, critical revision of the manuscript. SYH, EGK, and EJL: concept/design, acquisition of data, data analysis/interpretation, and drafting of the manuscript. RSW: concept/design, acquisition of data, data analysis/interpretation, and drafting of the manuscript. TKB: concept/design, acquisition of data, data analysis/interpretation, and drafting of the manuscript. SPO: concept/design, acquisition of data, data analysis/interpretation, and drafting of the manuscript. HIY: concept/design, acquisition of data, data analysis/interpretation, drafting of the manuscript, critical revision of the manuscript, and submission of the manuscript. DYS: concept/design, acquisition of data, data analysis/interpretation, drafting of the manuscript, critical revision of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

I confirm that my article contains a Data Availability Statement even if no data is available unless my article type does not require one.

ORCID

Ran-Sook Woo https://orcid.org/0000-0002-2128-9291
Tai-Kyoung Baik https://orcid.org/0000-0001-5174-2029
Hong-Il Yoo https://orcid.org/0000-0002-7405-471X
Dae-Yong Song https://orcid.org/0000-0001-5775-6288

REFERENCES

Akande, S.O. (2015) Dimensional accuracy and surface finish optimization of fused deposition modelling parts using desirability function analysis. *International Journal of Engineering Research & Technology*, 4(4), 196–202.

Albanese, M. (2010) The gross anatomy laboratory: a prototype for simulation-based medical education. *Medical Education*, 44(1), 7–9.

Allen, L.K., Eagleson, R. & de Ribaupierre, S. (2016) Evaluation of an online three-dimensional interactive resource for undergraduate neuroanatomy education. *Anatomical Sciences Education*, 9(5), 431–439.

Arantes, M., Arantes, J. & Ferreira, M.A. (2018) Tools and resources for neuroanatomy education: a systematic review. *BMC Medical Education*, 18(1), 94.

Bergman, E.M., van der Vleuten, C.P. & Scherpbier, A.J. (2011) Why don't they know enough about anatomy? A narrative review. *Medical Teacher*, 33(5), 403–409.

Bin, P., Conti, A., Buccelli, C., Addeo, G., Capasso, E. & Piras, M. (2016) Plastination: ethical and medico-legal considerations. *Open Medicine (Warsaw, Poland)*, 11(1), 584–586.

Brenton, H., Hernandez, J., Bello, F., Strutton, P., Purkayastha, S., Firth, T. et al. (2007) Using multimedia and Web3D to enhance anatomy teaching. *Computers & Education*, 49(1), 32–53.

Brooks, W.S., Woodley, K.T., Jackson, J.R. & Hoesley, C.J. (2015) Integration of gross anatomy in an organ system-based medical curriculum: strategies and challenges. *Anatomical Sciences Education*, 8(3), 266–274.

Campbell, R.I., Martorelli, M. & Lee, H.S. (2002) Surface roughness visualization for rapid prototyping models. *Computer-Aided Design*, 34(10), 717–725.

Challa, V.R., Thore, C.R., Moody, D.M., Brown, W.R. & Anstrom, J.A. (2002) A three-dimensional study of brain string vessels using celloidin sections stained with anti-collagen antibodies. *Journal of the Neurological Sciences*, 15(203–204), 165–167.

Chisholm, F. & Varsou, O. (2018) Resin-embedded anatomical cross-sections as a teaching adjunct for medical curricula: is this technique an alternative to potting and plastination? *Journal of Anatomy*, 233(1), 98–105.

de Kok, P., Kleverlaan, C.J., de Jager, N., Kuijs, R. & Feilzer, A.J. (2015) Mechanical performance of implant-supported posterior crowns. *The Journal of Prosthetic Dentistry*, 114(1), 59–66.

Henssen, D.J.H.A., van den Heuvel, L., De Jong, G., Vorstenbosch, M.A.T.M., van Cappellen van Walsum, A.-M., van den Hurk, M.M. et al. (2020) Neuroanatomy learning: augmented reality vs. cross-sections. *Anatomical Sciences Education*, 3(3), 353–365.

Estai, M. & Bunt, S. (2016) Best teaching practices in anatomy education: a critical review. *Annals of Anatomy*, 208, 151–157.

Fruhstorfer, B.H., Palmer, J., Brydges, S. & Abrahams, P.H. (2011) The use of plastinated prosections for teaching anatomy—the view of medical students on the value of this learning resource. *Clinical Anatomy*, 24(2), 246–252.

Gao, H., Liu, J., Yu, S. & Sui, H. (2006) A new polyester technique for sheet plastination. *Journal of International Society for Plastination*, 21, 7–10.

Garg, A.X., Norman, G.R., Eva, K.W., Spero, L. & Sharan, S. (2002) Is there any real virtue of virtual reality?: the minor role of multiple orientations in learning anatomy from computers. *Academic Medicine*, 77(10), S97–S99.

Ghassemifar, R. & Franzen, L. (1992) A double-embedding technique for thin tissue membranes. *Biotechnic & Histochemistry*, 67(6), 363–366.

Gibbons, I.R. (1959) An embedding resin miscible with water for electron microscopy. *Nature*, 184(4683), 375–376.

Haines, D.E. & Mihailoff, G.A. (2018) *Fundamental neuroscience for basic and clinical applications*, 5th edition. Philadelphia, PA: Elsevier.

Hwang, S.B., Chung, M.S. & Park, J.S. (2006) Method for preparing permanent brain slices and serial slice images for education and MRI correlation. *Anatomical Record. Part B, New Anatomist*, 289(2), 64–71.

Jones, M.V. & Calabresi, P.A. (2007) Agar-gelatin for embedding tissues prior to paraffin processing. *BioTechniques*, 42(5), 569–570.

Jones, D.G. & Whitaker, M.I. (2009) Engaging with plastination and the body worlds phenomenon: a cultural and intellectual challenge for anatomists. *Clinical Anatomy*, 22(6), 770–776.

Jongsma, L.A., de Jager, N., Kleverlaan, C.J., Pallav, P. & Feilzer, A.J. (2012) Shear bond strength of three dual-cured resin cements to dentin analyzed by finite element analysis. *Dental Materials*, 28(10), 1080–1088.

Kurth, T., Weiche, S., Vorkel, D., Kretschmar, S. & Menge, A. (2012) Histology of plastic embedded amphibian embryos and larvae. *Genesis*, 50(3), 235–250.

Latorre, R.M., García-Sanz, M.P., Moreno, M., Hernández, F., Gil, F., López, O. et al. (2007) How useful is plastination in learning anatomy? *Journal of Veterinary Medical Education*, 34(2), 172–176.

Morton, D.A., Peterson, K.D. & Albertine, K.H. (2004) *Dissection guide for human anatomy*, 1st edition. Philadelphia, PA: Churchill Livingstone, pp. 222–232.

Naaz, F., Chariker, J.H. & Pani, J.R. (2014) Computer-based learning: graphical integration of whole and sectional neuroanatomy improves long-term retention. *Cognition and Instruction*, 32(1), 44–64.

Opeskin, K. & Anderson, R.M. (1994) A device for cutting brain slices. *Biotechnic & Histochemistry*, 69(5), 253–256.

Pani, J.R., Chariker, J.H. & Naaz, F. (2013) Computer-based learning: interleaving whole and sectional representation of neuroanatomy. *Anatomical Sciences Education*, 6(1), 11–18.

Papa, V. & Vaccarezza, M. (2013) Teaching anatomy in the XXI century: new aspects and pitfalls. *Scientific World Journal*, 2013, 310348.

Riederer, B.M. (2014) Plastination and its importance in teaching anatomy. Critical points for long-term preservation of human tissue. *Journal of Anatomy*, 224(3), 309–315.

Sora, M.C., Latorre, R., Baptista, C. & López-Albors, O. (2019) Plastination—a scientific method for teaching and research. *Anatomia, Histologia, Embryologia*, 48(6), 526–531.

Sugand, K., Abrahams, P. & Khurana, A. (2010) The anatomy of anatomy: a review for its modernization. *Anatomical Sciences Education*, 3(2), 83–93.

Toga, A.W., Ambach, K., Quinn, B., Hutchin, M. & Burton, J.S. (1994) Postmortem anatomy from cryosectioned whole human brain. *Journal of Neuroscience Methods*, 54(2), 239–252.

Verhoeven, B.H., Verwijnen, G.M., Scherpbier, A.J. & van der Vleuten, C.P. (2002) Growth of medical knowledge. *Medical Education*, 36(8), 711–717.

von Hagens, G., Tiedemann, K. & Kritz, W. (1987) The current potential of plastination. *Anatomy and Embryology*, 175(4), 411–421.

Zarow, C., Kim, T.S., Singh, M. & Chui, H.C. (2004) A standardized method for brain-cutting suitable for both stereology and MRI-brain co-registration. *Journal of Neuroscience Methods*, 139(2), 209–215.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Lee, J-Y, Lee, J-C, Hong, S-Y, Kim, E-G, Lee, E-J & Woo, R-S et al. (2022) A new brain-cutting device and ultraviolet resin-mounted human brain slices as a teaching adjunct for neuroanatomy education. *Journal of Anatomy*, 241, 1477–1488. Available from: https://doi.org/10.1111/joa.13757