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Creation of a Virtual Atlas of Neuroanatomy and Neurosurgical Techniques Using 3D Scanning Techniques

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Introduction

Neuroanatomy is one of the most challenging and fascinating topics within the human anatomy, due to the complexity and interconnection of the entire nervous system.[1] Students are required to learn not only anatomical structures, but also be able to recognize their topography, spatial relationships, and clinical significance.[2] Traditionally, neuroanatomy has been represented with 2-dimensional (2D) images, which makes it difficult to understand the 3-dimensional (3D) architecture and correlation among the different structures of the nervous systems.[3] Specifically, surgical neuroanatomy is even more challenging due to the intricate relationship among microscopic structures that should be properly recognized using different corridors, angles, and perspectives within the anatomical configurations that may be presented. Acquisition of this anatomical knowledge and its successful clinical application requires years of practice.[4]

Cadaveric dissections have been utilized to improve our understanding of human anatomy since the third century BC and still, it is a crucial source of knowledge to advance in neurosurgical training. Indeed, surgical simulations in cadaveric dissection are considered the gold standard in improving the comprehension of 3D neurovascular structures location and creating necessary surgical skills.[5-6] These skills include depth perception, 2D and 3D vision orientation, sensitive movements in limited environments,[7] bimanual coordination, and hand-eye coordination.[8-9] Several studies have proven that neurosurgical proficiency attains an expert level after approximately 10,000 hours of focused practice.[10,11] To reach such a goal in a certain field, a person should dedicate 5 hours/day, 6 days/week, 48 weeks/year for 6.9 years.[11] This is more than the neurosurgical residency program in Italy and most European countries. Moreover, access to laboratories for cadaveric dissections is limited due to a worldwide lack of cadaveric donors, the high and increasing costs of materials, the reduced number of dedicated neuroanatomy laboratories, and international travel restrictions due to the

coronavirus pandemic. All these factors have contributed to decreased hands-on experience using cadaveric donors to improve surgical neuroanatomy learning.[12-14] As a result, these recent limitations have paralleled the rapid adoption of new technologies to maximize the use of the existing cadaver supply.[15-17]

Stereoscopy (SS) offers the possibility to integrate the perception of depth resulting from binocular vision and has been explored for years as a crucial tool for educational and practical purposes. Although the beginnings of SS can be traced back to Da Vinci's work,[18] only in the last decades has gained more popularity. The awareness of the benefits of SS, such as the easier discrimination of the structure, improved surface detection, and depth judgment, has led to increased use of SS in teaching medical students and residents, in a higher number of programs.[18] Several studies have proven the advantages of SS[19-20] and the use of stereoscopic imaging and videos in lectures and publications has increased in the last years. Moreover, in neurosurgical practice, the use of 3D (i.e., stereoscopic) microscopes and endoscopes has gained high popularity and represents a valuable resource for students, observers, and residents in the operating room.

With the advance in 3D technologies, volumetric models (VMs) – a virtual reconstruction of an object using 3D coordinates - are the new frontier. The first anatomical models can be traced back to 1988 with the Visible Human Project sponsored by the National Library of Medicine, of the United States of America,[21] which was designed as the first morphometric dataset that can be used to generate a submillimeter-thick reconstruction of the human anatomy using cryosections. The Visible Human Project is a public domain that contributed to anatomical research and education.

In the neuroimaging field, VMs are commonly built from DICOM (digital imaging and communications in medicine) and are primarily used for diagnosis and surgical planning. Conventional imaging studies (i.e., MRI or CT scans) generate low-resolution VMs due to the

thickness of the slices (1mm for a CT scan, 1.4mm for a 7T MRI). The use of VMs obtained from DICOMs in neuroanatomy education and research oftentimes requires a postprocessing workflow that involves the surface reconstruction and texture simulation performed by 3D artists.[22-23] Although these VMs are very useful to understand neuroanatomy, they require the expertise of a 3D artist which may be time-consuming and highly expensive. Additionally, the final representations might lack of fidelity due to the subjective interpretations of the artists.

Commercially available 3D scanning techniques are accessible alternatives to get 3D reconstruction of the anatomy and have gained popularity in the field of teaching neuroanatomy. Essentially, 3D scanning describes the process by which a detector traverses an object and collects data on its shape, texture, and color before digitizing it.[24] Two popular techniques for acquiring this initial 3D blueprint of a target object are photogrammetry (PGM) and structured light scanning (SLS). PGM is a process by which the metrics of common surface points are taken from photographs to create clouds of colorized coordinates that will subsequently be triangulated to construct the VM. Although methods for obtaining 3D data from 2D photographs have been available for half a century,[25] PGM applications have appeared only sporadically in neurosurgery.[26-27] However, recent advances in PGM software have made it a potentially practical alternative to dedicated surface scanners.[28] Its principal advantages are portability, few pieces of equipment required, and intuitive workflow, all of which can reduce the overall research costs. Notable applications of PGM include producing film and video games, preparing topographic maps, and planning architectural designs.[29-30] In contrast, 3D scanning techniques such as SLS represent a portable method to rapidly obtain 3D anatomical data using structured light or lasers to capture surface topography.[28] The scanner will typically be connected to a computer that automatically registers and reconstructs the coordinated frames.[31] Subsequently, this rough image can be fine-tuned and post-processed to prepare it for export to a 3D modeling server or 3D printing modality. Popular applications of such

modalities include Microsoft Kinect (Microsoft Corp., Redmond, Washington, USA), biometric identification software (e.g., face, and retinal scans), and reverse-engineering industrial tasks.[3] VMs generated by 3D scanning techniques provide high-quality color and texture, feedback, and surface reconstruction which accurately replicate reality. Recently, several authors have published different scanning techniques to create VMs from cadaveric dissections.[3,26-28,32-34] Reconstruction of VMs from both anatomical and surgical dissection can be a crucial tool in understanding and learning neuroanatomy for medical students, residents, and young attendings. Moreover, the possibility to interact with these models either in a virtual (i.e., extended reality that involves augmented reality (AR) and virtual reality (VR)), or physical manner (i.e., 3D printing), is a cutting-edge step for neuroanatomy research and learning.

In this project, we aimed to describe the use of different currently available 3D scanning techniques and the application of a workflow to create a virtual atlas of neurosurgical anatomy. The atlas will show relevant topics of neurosurgical anatomy divided into collections such as neurosurgical approaches, skull base, cortex and fiber tracts, and spine operative anatomy. The VMs will be hosted in an online platform with VR and AR features to allow also virtual interaction and facilitate the use and understanding of the models.

Material and Methods

Anatomical Dissections

Dissections were performed on post-mortem heads and brains at the Stanford NeuroTraIn Center, Stanford University, and at the Skull Base and Cerebrovascular Laboratory (SBCVL) at the University of California, San Francisco (UCSF). The heads were embalmed with 4% formaldehyde solution and injected with red and blue latex for arteries and veins, respectively. Heads were stored in 100-75% alcohol solution before and during the dissections to preserve the quality of the tissues. Brains were fixed with a 4% formaldehyde solution for at least 4 weeks and then prepared for white matter dissection. After washing the brain, it was placed in water and frozen (-20C) for 2-3 weeks. After a defrosting time of 1-2 days, the freezing cycle was repeated a second time (-20C). During dissections, the brains were stored in 100-75% alcohol solution in the freezer to keep the tissue firm.

The heads were pinned using a Mayfield holder (Mizuho, Tokyo, Japan) and placed in a surgical position according to the approach and area to expose. An operative microscope (Kinevo 900, Zeiss, Carl Zeiss AG, Germany), endoscope (Karl Storz, Tuttlingen, Germany), surgical drills (Stryker, Kalamazoo Michigan, and Medtronic, Dublin, Irland), and instruments (macro and micro) were used for the dissections. The most relevant neurosurgical approaches were performed including pterional, fronto-orbito-zygomatic, retrosigmoid, interhemispheric (anterior, middle, and posterior), suboccipital, far-lateral, extreme-lateral, endoscopic endonasal approach, endoscopic transorbital, anterior and posterior cervical. White matter dissections were carried out to expose the principal fiber tracts of the cerebrum and brainstem. After performing microdissections of embalmed cadaveric specimens, we followed a standardized workflow to record the relevant neurosurgical anatomy. The major steps consisted of capturing 2D/SS media and subsequently setting up specimens in a diffuse-light studio setup

for scanning. The fundamental process underlying both SLS and PGM techniques was as follows: a series of images of the target specimen's surface were acquired from multiple viewpoints using 360º rotation of an arbitrary vertical axis—at the superior, medium, and inferior elevations of the camera concerning the specimen. Processing software was used to superimpose the acquired images and measure the intersecting tie points to triangulate their location in 3D space, thereby creating a VM. Finally, lighting is an essential consideration, because surface detection is the fundamental mechanism by which these techniques operate. The object remained static, and the lighting diffused. Between two and three photographic studio flashlights were set up around the specimen to reduce the amount of shadow. An extra camera video light was added when needed as well as polarized filters for the lens. Extra light and filters were particularly useful for skull bones (e.g., sphenoid, temporal bone) reconstruction. Objects that are glossy, metallic, or transparent were covered with talcum powder or scanning spray to avoid reflections. Round target stickers were also applied to the background of objects with a homogenous surface and/or texture to help the scanner detect the surface. After securing the specimens on a turntable, the scanning process was initiated.

Photogrammetry workflow

The PGM workflow consisted of 3 steps: 1) image capture, 2) preprocessing (optional), and 3) processing. Because the image was taken in 2D, the surface area that can be captured was limited by the camera's field of view. To obtain additional surface angles, the assembly must be moved relative to the surface. Image capture proceed using three methods: 1) taking multiple photographs with a handheld camera moving relative to the specimen or a point of interest between photographs; 2) rotating the specimen on a turntable with the camera fixed on a tripod; and 3) extracting frames from a video, again with the camera moving relative to the specimen. The camera used was a professional camera, such as a digital single-lens reflex (DSLR), or

mirrorless, with a professional lens with a 50mm focal length. Other cameras that were used are the smartphone, endoscope and surgical microscope. However, the selected camera should ideally have a high megapixel count (>12 megapixels), with a lens that can provide a clear and static view of the entire surface. In our experience, we believe that the first 2 methods involving the handheld camera and tripod were the most efficient for image capture. The DSLR camera or the smartphone was used for models of the whole specimen (extended and superficial dissections); the endoscope or the microscope was used for deep surgical corridors, such as endonasal or middle and posterior fossa approaches.

1. *Image Capture*

    a. *Whole Specimen*

First, the specimen is placed on a black cloth and secured on a turntable (Figure 1). Next, the operator takes a video or a series of photographs from the superior, middle, and inferior aspects of the specimen, rotating the object 360º on the turntable for each view of the specimen (around 45 photographs should be acquired about the axis from each aspect). When all the specimen surfaces cannot be acquired in the same position, the orientation of the specimen should be adjusted, and the pictures or video should be taken again as described above. During this process, the camera or smartphone should be fixed on a tripod and only moved for each photograph series to cover the specimen surface.

A different method consists of moving the camera in the three axes around the specimen or interested region. This is recommended when using the smartphone and for areas with fewer detail or no deep structures (e.g., skin, bone). In the video option, capturing a 45-90 second video at a frame rate of 24 frames/second will yield ~1000-2000 frames. Therefore, setting a frame step of ~10-25 should yield ~80 images. For specimens with different levels of dissections, an extra set of close-ups (zoomed) pictures (180-360º turn) of the part with more

details were taken. Whenever possible pictures were saved in .raw format or the highest output resolution available.

Figure 1. Standard PGM setup for whole specimen.

b. Deep Corridors

A rigid endoscope with a 30º lens or a surgical microscope was used to capture the images from multiple viewpoints via rotation around an arbitrary vertical axis through the center of a structure of interest. Images were captured at superior, medium, and inferior elevations of the camera.

To improve the texture of the final VM, additional images of various points of interest were captured with the scope midway from the entrance of the corridor to the skull base structures. These photographs were taken to ensure that the entire desired surface was captured with sufficient partial overlap between the different pictures—a step that is crucial for later alignment. Each surface point is represented in at least 2 to 3 images, with 1 taken in the direct line of the normal to the surface in the region of the location of interest and 1 to 2 images taken with slight displacement from the normal to the surface in the region of the point of interest. By extension, this necessitates an overlap of at least 60% (with 80% preferred) of a captured area between consecutively taken photographs. With sufficient correspondence, the processing software can later superimpose the acquired images and measure the intersecting tie points to triangulate the location of a point in 3D space, thereby creating a 3D model.

Figure 2. Standard photogrammetry setup for deep corridors.

2. Pre-processing

Although an optional step, pre-processing the raw image data set yielded a superior result by improving the visibility of the details in the shaded and lit areas and increasing the micro-contrast (Figure 3). To improve the quality of the final image, the exposure and white balance were fixed such that the parts in the shade were lightened and the lit areas darkened. Chromatic aberrations and noise were then be removed, and the image sharpened. For endoscopic pictures, a crucial step was to crop the imaging from the black background. All processes were run in 16-bit and exported in 100% quality 8-bit joint photographic experts group format (.jpeg), 16-bit tag image file format (.tiff), or 16-bit portable network graphic format (.png) using two different image processing software (DxO Photolab 3, [DXOMARK Image Labs SAS, Paris, France] and Lightroom, [Adobe Systems, San Jose, California, USA]).

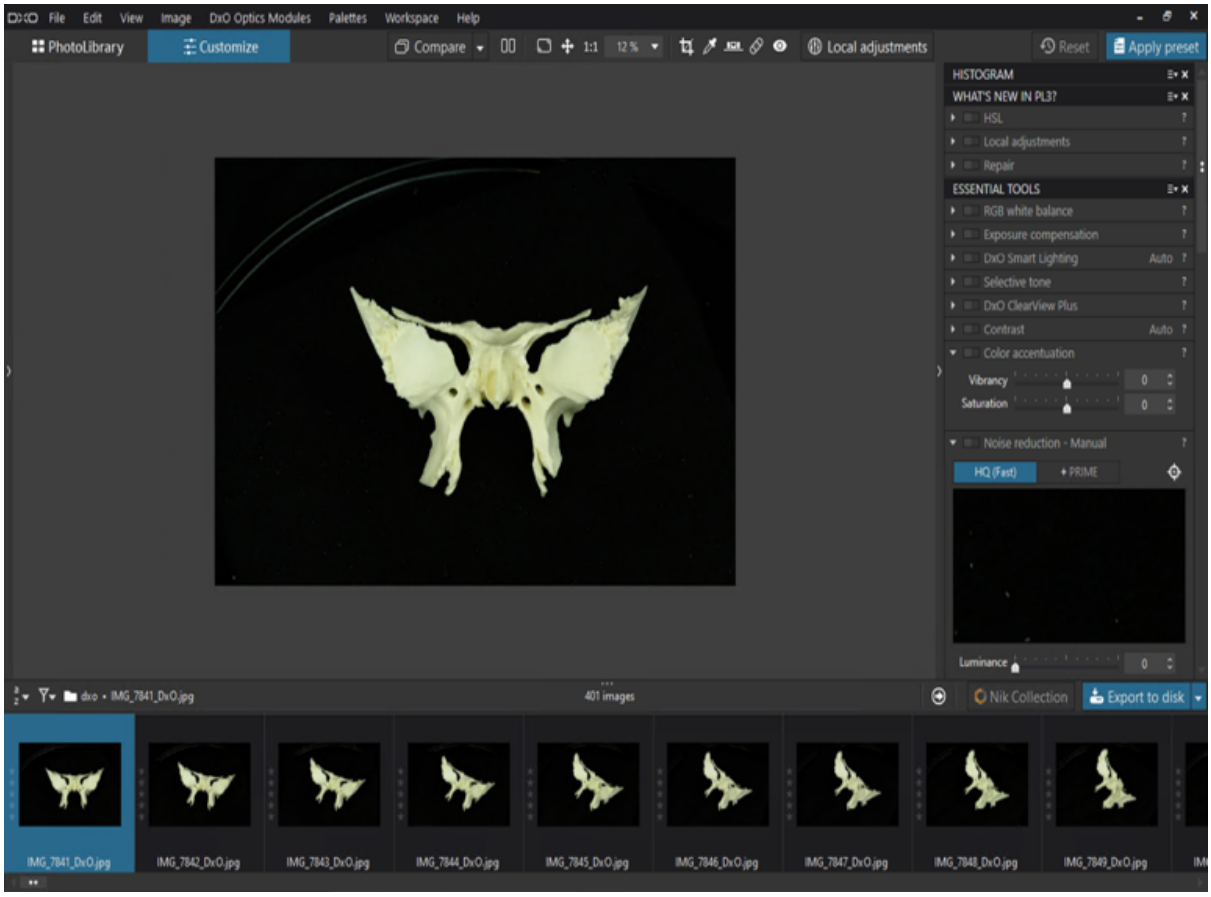

Figure 3. Pre-processing with DXO-PhotoLab.

3. Processing

Processing describes generating the mesh and texture data from the images. The images were uploaded to PGM software and put through a sequence of processing steps. A cache location was set to a dedicated large solid-state drive (512 Gb) or on a hard disk drive. The images were first subjected to automated masking, followed by manual correction of the automatically generated masks. This step excludes the background during model construction. Image grouping with low overlap were enabled to help avoid incorrect camera and lens estimations. To construct the digital model using Reality Capture (Reality Capture Beta 1.0 [Capturing Reality, Bratislava, Slovakia]) the masked photographs were processed through alignment, geometric or mesh reconstruction, and texturing step (Figure 4). These processes ran in a semimanual mode. The reconstruction application will compare the shapes in the photographs (alignment step) to generate a high-resolution 3D mesh. During geometric reconstruction, sharp reconstruction was used to prevent the software from adding extra geometry to the mesh.

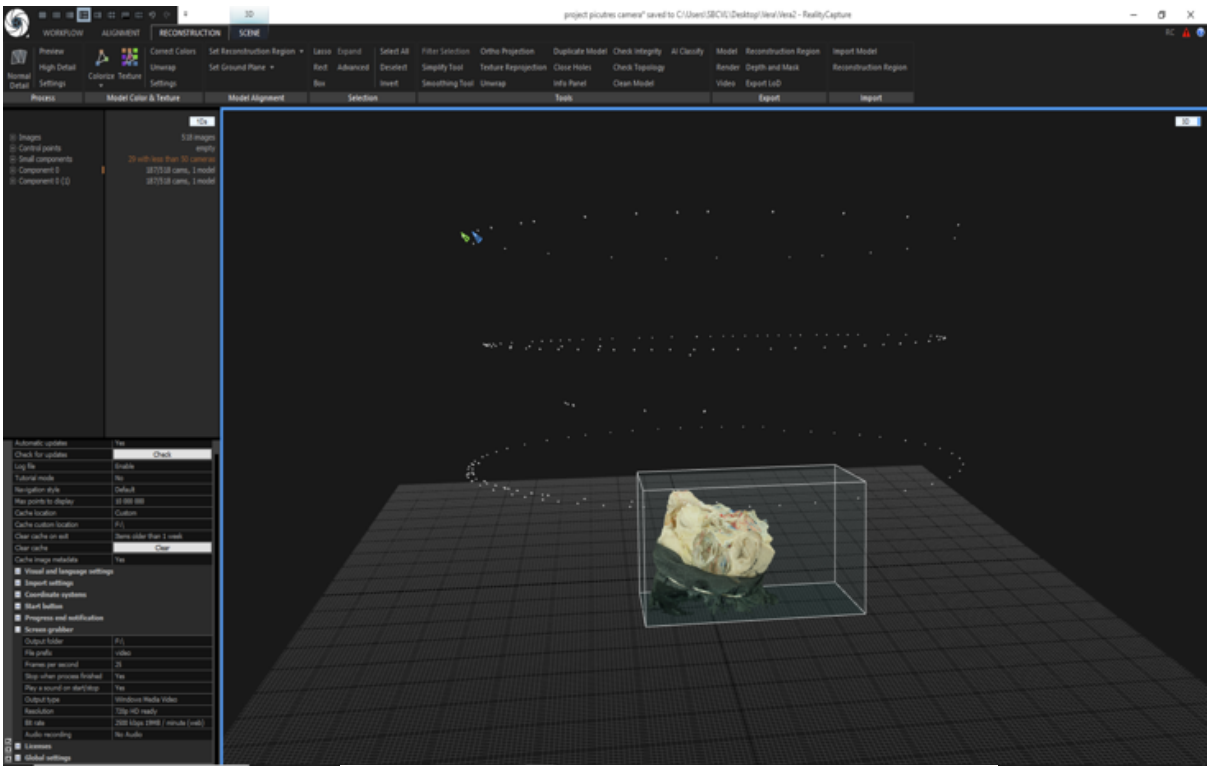

Figure 4. Processing with Reality Capture.

With Metashape software (Metashape v.1.5.1 Agisoft LLC, St. Petersburg, Russia), a similar

process was used following these steps: alignment, dense cloud, mesh (Figure 5). The reconstruction was then decimated to yield a simpler mesh with fewer polygons (500,000 - 1,000,000), smoothed, and fixed from holes. The mesh was also exported in a wavefront data format (.obj) file to further post-processing (see postprocessing section). Afterward, using either software, texturing of the mesh was accomplished which consist in superimposing a precisely shaded and colored representation of the specimen over the geometric reconstruction (i.e., the color contained in the photographs is transferred to the textures used on the surface of the mesh). Then the VM was exported in wavefront data format (.obj) file with the accompanying material files (.mtl format) and texture files (.png format). The steps for processing the image data sets obtained from videos or photographs are identical. Additional images of the most geometrically complex surfaces, including partially or entirely hidden surfaces and surfaces with fine detail, were acquired to improve the completeness and accuracy of the final volumetric model. The image sharpness and depth of field should be maximized.

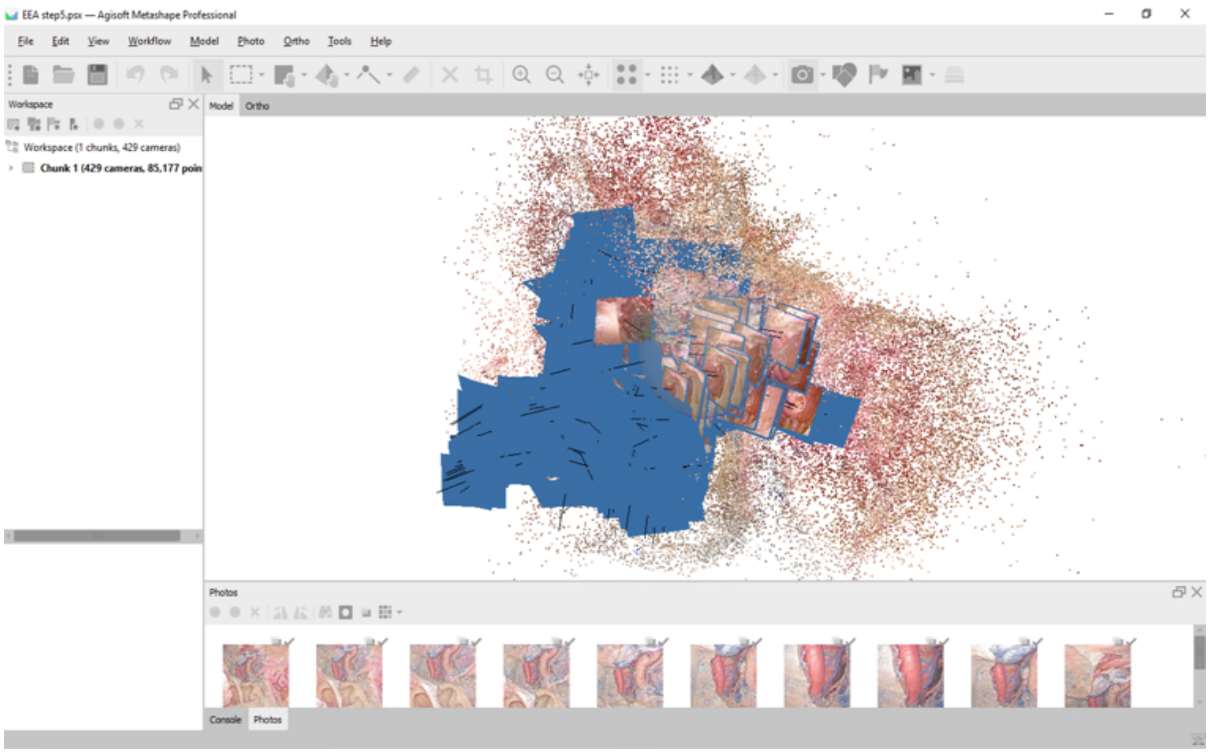

Figure 5. Processing with Metashape.

Cloud-based Photogrammetry

Polycam (Poly, Altadena, California) software was used to create some VMs of dissections as well. Image capture and pre-processing were done following the workflow described in the PGM section. Then the pictures were uploaded to the platform, the auto mask feature was turned on, and the quality was set to raw. Once the VM with texture is generated by the platform it can be exported as .obj, post-processed, and uploaded to different platforms.

Structured Light Scanning

The 3D scanning workflow for SLS involved 1) scanning and 2) processing. The specimen was first placed on a black cloth on top of a turntable (if unstable, wax support should be used).

1. *Scanning*

The SLS scanner (Artec Space Spider [Artec, Luxembourg City, Luxembourg]) was held at an optimized distance (9-18 cm) from the surface of the specimen, as determined by the preview screen shown by the scanning software (Artec Studio 12 [Artec, Luxembourg City, Luxembourg]). The turntable was smoothly rotated such that the specimen rotates relative to the scanner. Multiple scans were then acquired. For surface capture, three scans were conventionally acquired. For capturing specimen surfaces that cannot be fully scanned in a single orientation on the turntable, 6-12 scans were acquired by adjusting the orientation of the specimen. The scanner was also moved over the surface of the static object. Regardless of the method used, the scans were taken with 360º rotations of the specimen about an arbitrary vertical axis passing through the center of the surface from the superior, middle, and inferior aspects.

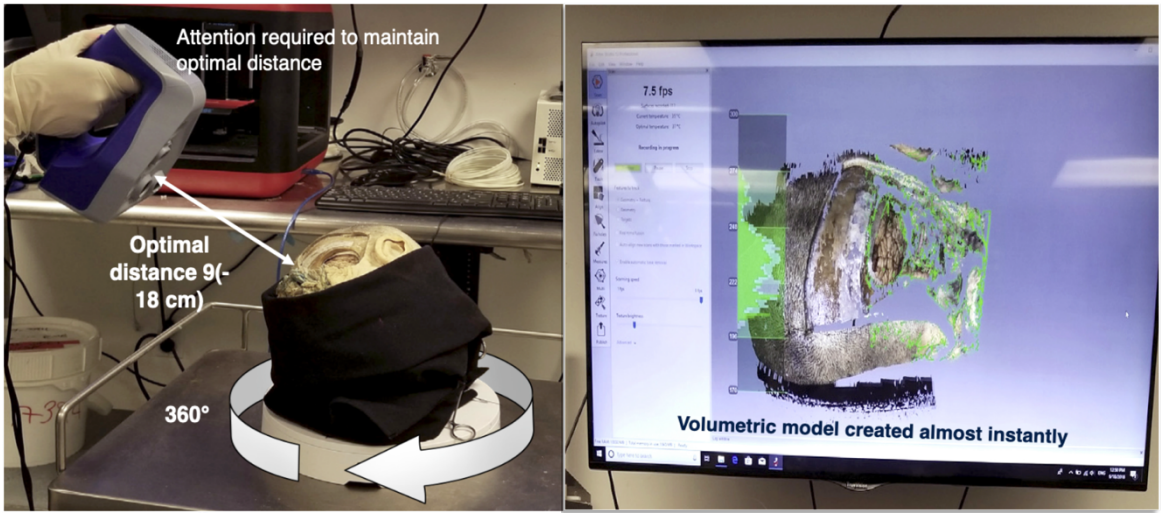

Figure 6. Scanning and processing with Artec Space Spider and Artec Studio.

2. *Processing*

The software captured both geometrical features and the color texture of the object (Artec Studio 12, [Artec, Luxembourg City, Luxembourg]). Overlap on the scans was achieved with the approximate aim that each element is present in three images. Each frame was registered during processing. For rigid specimens (e.g., bone), rigid alignment was conducted. For nonrigid specimens (e.g., dissected brain), the specimen should be frozen and semi-thawed to facilitate the use of the nonrigid alignment tool. The color texture should permit robust auto-alignment of the scans. Registration between the scans were performed and the outliers were removed. The scan views were merged with sharp fusion to create a watertight polygon mesh file. This semiautomatic process was performed using the 3D scanner's proprietary software. The mesh was decimated to 500,000-1,000,000 polygons and smoothed, if necessary. Finally, the mesh was exported using the same file and formatting as described for PGM.

The different workflows described were compared in terms of time, quality of the reconstruction, and prices of the material.

Post-processing

Oftentimes topology of the VM needs to be fixed before projecting the texture using 3D modeling software (MeshMixer, version 3.5 [AutoDesk, Inc., San Rafael, California, USA] or Zbrush 2021.5.1, Pixology Inc., California, USA; Blender 2.82, Blender Foundation, Amsterdam, Holland). This process involved manual 3D sculpting and semiautomatic re-topology. After repairing the mesh with 3D modeling software, a clean mesh can be exported (Figure 7).

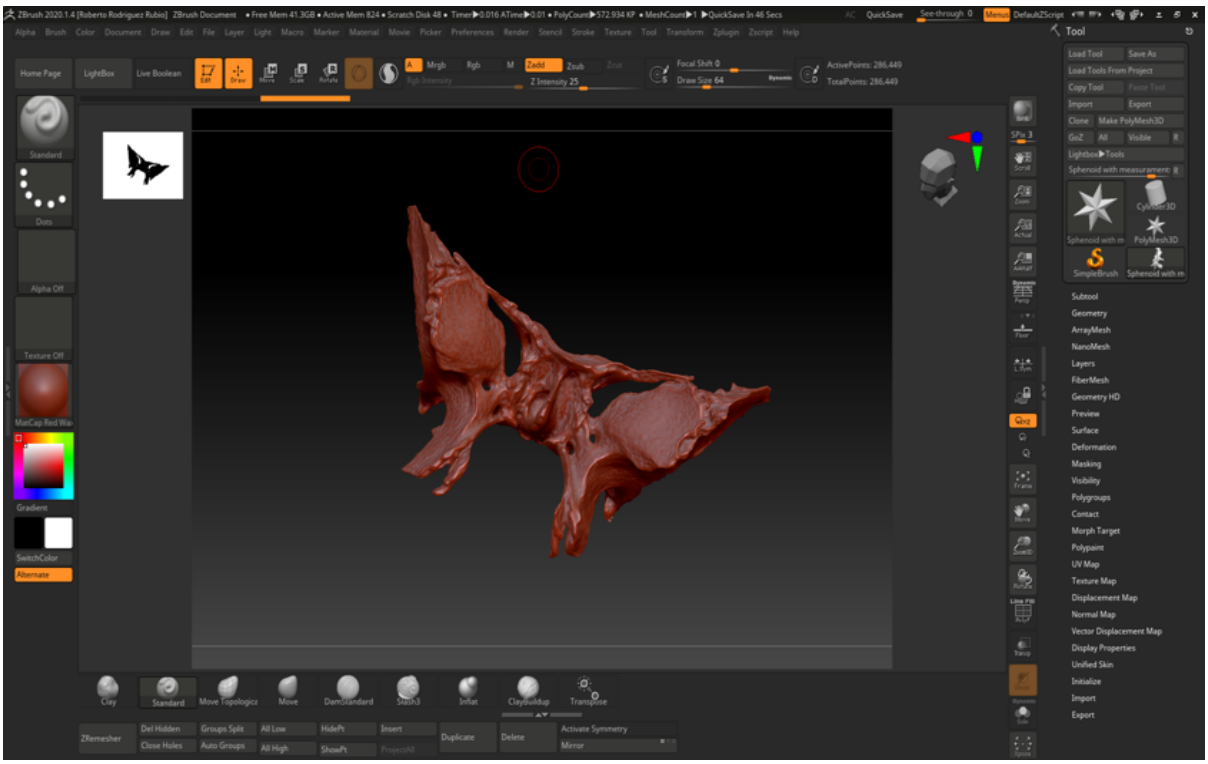

Figure 7. Mesh post-processing using Zbrush.

The mesh was then imported into the PGM software to proceed with the texturing step on the modified mesh. Once the VM was obtained, the texture was imported into a 3D texturing software, Substance painter (Substance Painter [Adobe Systems, San Jose, California, USA]), to fix errors with clone stamping and texture projection tools (Figure 8). The final based color texture was saved as a .png file in 4k resolution.

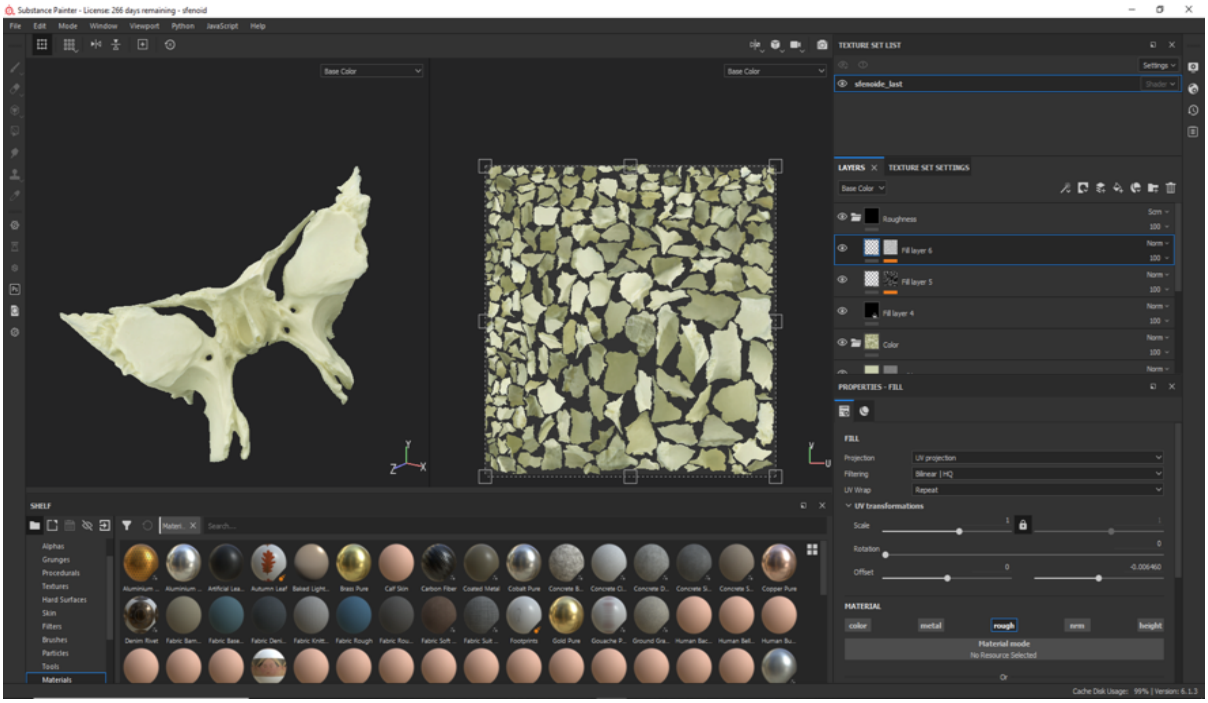

Figure 8. Texture post-processing using Substance Painter.

Fiber tracts DICOM Imaging Reconstruction - DSI studio

DSI Studio (DSI-studio, Pittsburgh, Pennsylvania) is a tractography software that maps brain connections.[35] This software uses a collective implementation of several diffusion MRI methods, including diffusion tensor imaging, generalized q-sampling imaging, q-space diffeomorphic reconstruction, diffusion MRI connectometry, and generalized deterministic fiber tracking. Using DSI studio, the user has access to a tractography atlas created from a population-averaged structural connectome that includes both major and minor pathways. (Figure 9). Both single tracts and bundles were exported as obj. files to integrate white matter dissections models, such as the perisilvian pathways, the internal and external capsule, the optic radiation, the corpus callosum, the cingulum, the fornix, and the anterior commissure.

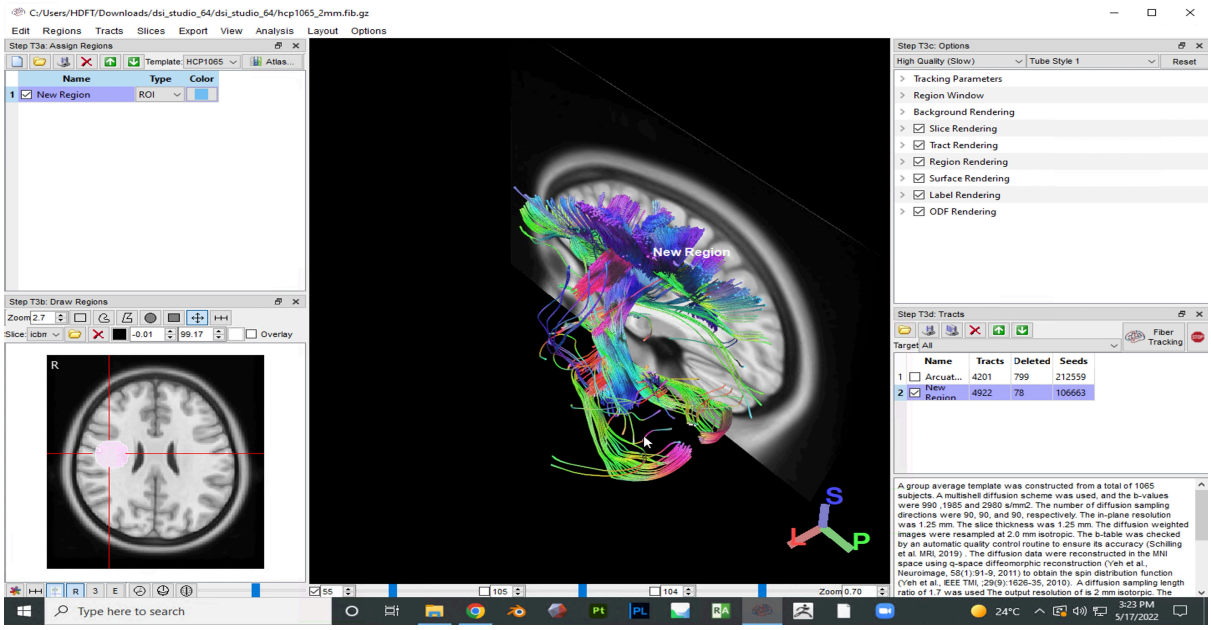

Figure 9. Fiber tracts reconstruction using DSI-studio

Commons License Materials

A repository of 3D reconstruction of individual anatomical structures BodyParts3D (BodyParts3D, © The Database Center for Life Science licensed under CC Attribution-Share Alike 2.1 Japan) was used to obtain models of intracranial structures were used (e.g., bone, ventricle, arteries).

Compositing and Rendering of VMs

VMs from PGM, SLS, DSI-studio, and common license material were uploaded in 3D software (Blender 2.82, Blender Foundation, Amsterdam, Holland) to create 2D or stereoscopic renders and animations. Blender is a 3D computer graphics software toolset used for creating animated films, visual effects, art, 3D-printed models, motion graphics, and interactive 3D applications. Using this software, we were able to import and work with several models cotemporally. This allowed us to articulate skull bones, combine different models, and integrate white matter dissection models and tracts. Also, cinematic videos depicting the VM in different stages of microdissection were created. VMs downloaded from the common license material were also

post-processed on Blender. This allowed the integration of different structures (e.g., cervical vertebrae, occipital bone, medulla) to recreate a specific anatomical region. The videos were exported as .mp4 files, and the combined models were uploaded to an online platform as blender files.

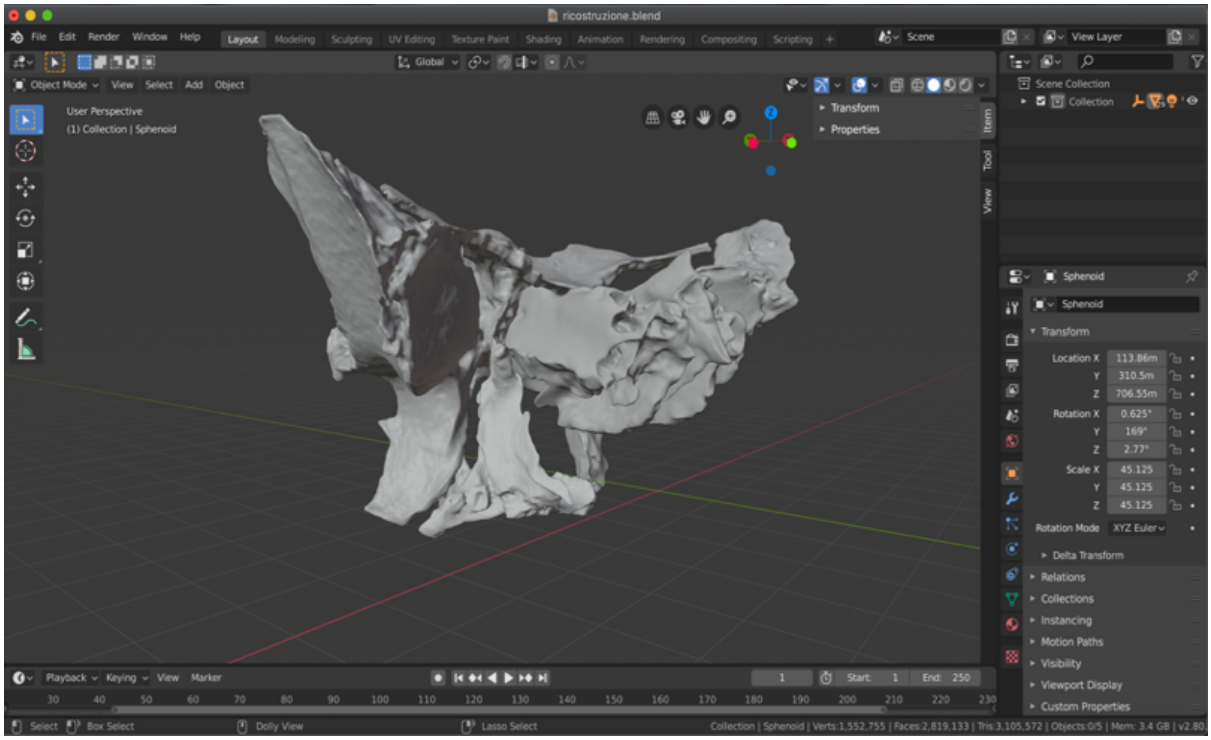

Figure 10. Rendering with Blender.

Platform

We used a web-based, 3D models viewer app (Sketchfab [Sketchfab Inc., New York, New York, USA]) to upload our VMs, allowing for a truly immersive and interactive experience of the different anatomical structures. The VMs with relevant annotations were then rendered in real-time, and the lighting and positioning of the models were manipulated to highlight anatomical regions of interest. Moreover, it is possible to modify the textures (color, glossiness) and opacity of each model. Using a free web page, QR code were generated and added to the collection to easily access the VMs.

Results

Virtual Atlas

All the 3D scanning methods yielded models that upheld suitable clarity and structural integrity for anatomical education, scientific publications, and surgical illustration. More than 200 models were generated using the described workflows. Dissections have been divided into collections regarding the specific approach, area of dissection, white matter anatomy, and bone anatomy. The VMs generated were used for several publications to describe the step-by-step of a specific neurosurgical approach and to enhance the understanding of an anatomical region and its function.[36-47] These models were used to train medical students, residents, and young neurosurgeons. The objective assessment of the increased understanding of neuroanatomy was not included in this project. Nevertheless, the publications included in the Immersive Surgical Anatomy Collection published in Cureus have reached 46.415 views and were cited more than 10 times (updated November 2022). Three models are currently used for a VR surgical simulation app under development. Figures 11-14 are representative of the different collections (scan QR code with your smartphone to access the models).

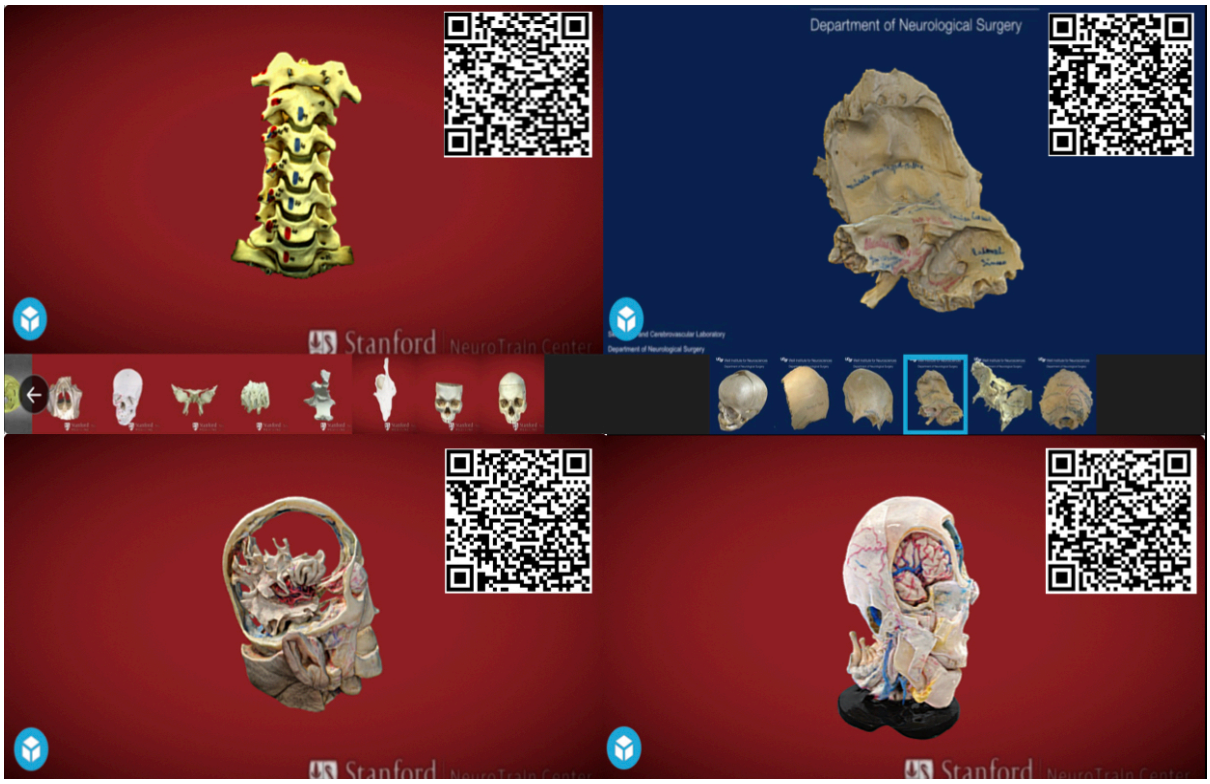

Figure 11. Collections of Bones with PGM, Bones with SLS, Anatomical dissections and Open Skull Base approaches.

Figure 12. Collections of White matter, Craniometric points, Craniocervical junction and Hypothalamic nuclei anatomy.

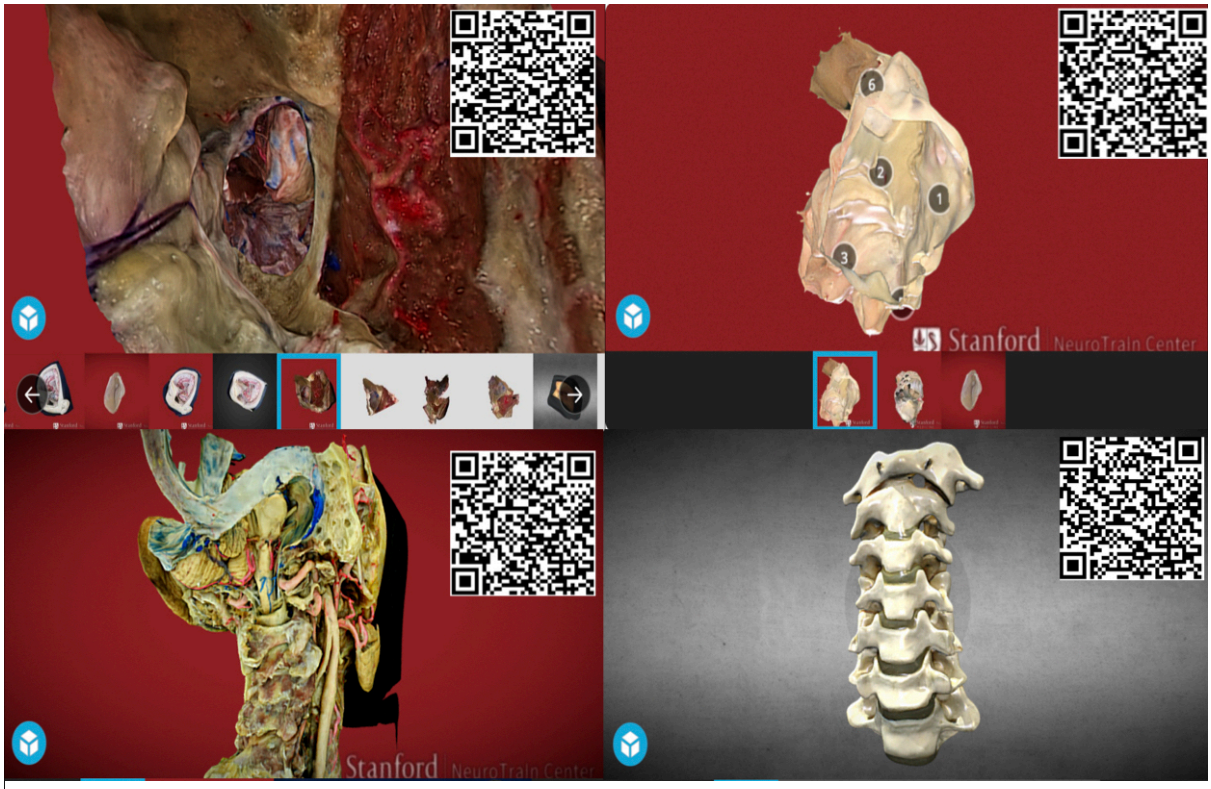

Figure 13. Collections of lateral transorbital approach, medial transorbital approach, suboccipital approach and anterior cervical approach.

Figure 14. Collections of pterional approach, fronto orbitozygomatic approach, Endoscopic endonasal approach and retrosigmoid approach.

3D scanning techniques

Characteristics of PGM and SLS techniques are briefly summarized in Table 1. In Tables 2 and 3 the material and software used for the workflows are listed with price comparison. Efficiency in terms of the time for reconstruction using PGM software and SLS is listed in table 4.

Table 1. Summary of the workflow for photogrammetry and structured light scanning

Step	*Photogrammetry*	*Structured light scan*
Image capture	Camera or phone: Pictures or video of the object from the superior, middle, and inferior aspects Endoscope: Move around a point of interest with 60-80% of overlap	Move the scanner around the specimen in the superior, middle, and inferior aspect
Pre-processing	Optimize photo (color, saturation, exposure, crop)	Frames are obtained in.scan format
Processing	Construction of the model automatic or semiautomatic. Perform alignment, reconstruction, and texture of the model.	Semiautomatic workflow includes scan alignment, outlier removal, texture addition, mesh decimation/ smoothing, and exporting.
Post-processing	Improve mesh (close holes, smooth) and texture	Improve mesh (close holes, smooth) and texture

Table 2. Pricing* of the photogrammetry workflow material and software (most of the software have student/teacher discounts or free license).

Material	*High budget*	*Low budget*
Camera	Mirrorless Camera ~$3500 (Sony alfa 7R)	Smartphone: ~$100-1500 (Motorola or iPhone)
Tripods and lighting	Manfrotto Tripod $250 Dazzne D50 Lights $230	Amazon Basic Tripod $15 Limo Studio Light $80
Turntable	Foldio360 $139	Lazy Susan Turntable ~$10-20
Imaging pre-processing	DXO Photolab $129 Adobe Lightroom $119.88/year	GIMP (free)

Processing	Metashape, Agisoft Professional $3499 – Standard $179 Capture Reality – Enterprise $3750 Pay-Per-Input License $10-20	Meshroom (free) – Windows and Linux 3DF Zephyr free (free) MicMac (free)
Computer	PC or Desktop (CPU: 4 - 12 core Intel, AMD or Apple M1/M2 processor, 2.0+ GHz. RAM: 16 - 32 GB. GPU: NVIDIA or AMD GPU with 1024+ unified shaders.) $1500	PC or Desktop (CPU: 4 - 12 core Intel, AMD or Apple M1/M2 processor, 2.0+ GHz. RAM: 16 - 32 GB. GPU: NVIDIA or AMD GPU with 1024+ unified shaders.) $1500
Post-processing	ZBrush $895 Substance Painter, Adobe $299.88/year	Meshmixer (free) Blender (free)

* All the prices are up to date with the program's webpage (November 2022).

Table 3. Pricing* of the structured light scanning workflow material and software (most of the software have student/teacher discounts or free license).

Material	*High budget*	*Low budget*
Scanner	Artec Space Spider~$24800	LiDAR Smartphone ~1500-2000
Processing	Artec Studio $2900	Polycam $54.99/year
Computer	PC or Desktop (CPU: Intel Core i5-11, Windows 7-10(x64), RAM: 18-32GB, GPU: Ndivia card with 2-4GB of VRAM) $1500	Any computer $500
Post-processing	ZBrush $895 Substance Painter, Adobe $299.88/year	Meshmixer (free) Blender (free)

*All the prices are up to date with the program's webpage (November 2022).

Table 4. Time for VM reconstruction using PGM and SLS.

Step	Modality	Time
Image capture	Camera	30-60 mins
	Smartphone	10 mins
	Endoscope	15 mins
	Artec Spider	20 mins
	LiDAR	15 mins
Pre-processing	DXO Photolab	100/1h
	Adobe Lightroom	100/1h
Processing	Metashape	300 pictures/6h
	CaptureReality	300 pictures/1h
	Artec Studio	4-6 scans (800 frames per scan) /1h
	Polycam	250 pictures/15min

Instructions to see the VMs

The following instructions can be used to manipulate all models: to move, left click and drag; to zoom in and out, use the mouse scroll. For smartphones and VR- ready computers, click "view in VR" (glasses icon); to view annotations, click on the numbers, to move around the object, tap or press the trigger on the floor using the blinking yellow circle as a pointer. For mobile AR, click on the AR icon (cube) in the top right corner and aim at a horizontal flat surface; once the surface is detected, tap on it to place the model

Discussion

The History of Volumetric Modeling

Medical imaging and computer graphics are 2 frontiers that have fundamentally changed the way we perceive, interact, and learn about human anatomy.[48] While it is commonly thought that such innovations only came to fruition in recent decades, the conceptual predecessor of this technology, SS, has been under investigation since antiquity. Based on the principle of stereopsis—the perception of depth arising from binocular vision—functional applications of SS has been pondered by scientists, thinkers, and physicians as diverse as Euclid, Galen, and Ibn al-Haytham.[48-49] Their respective insights came to a head in 1832 when scientist Charles Wheatstone developed the prototype of a stereoscope—a device able to reproduce stereopsis and yield the illusion of "3D".[50] His innovation was applied in many fields, including medicine, as physicians saw the stereoscope as a tool uniquely able to illuminate the labyrinthine and intricate details of human anatomy. The first prominent example of this effort was Daniel John Cunningham's Stereoscopic Studies of Anatomy, published in 1905, and it was the first 3D atlas.[51] Over the years, similar collections specific to neuroanatomy were produced.[52-53] The individual who ultimately played a pivotal role in popularizing the synthesis of surgical neuroanatomy and stereoscopic viewing was Albert J. Rhoton, whose laboratory pioneered a variety of neurosurgical techniques and exposures. Rhoton utilized stereoscopic images to supplement academic papers and lectures, introducing to an entire generation the utility of the SS perspective.[54-57]

Since these first 3D neurosurgical reports, stereoscopic technology has evolved to include stereoscopic intraoperative video recording, VMs, and endoscopic displays. In conjunction with new digital imaging modalities, the current generation of physicians is at the forefront of a revolutionary development whose roots can be traced from Euclid to Rhoton.

Modeling in Neurosurgery

Computer graphics is a rapidly developing field with applications in science, engineering, architecture, entertainment, and medicine.[58-60] Because most neurosurgical procedures and corresponding pathologic entities involve intricate, minute anatomical structures that cannot be easily perceived, neuroimaging technology (e.g., CT, MRI) has become a fundamental tool in the surgeon's clinical armamentarium.[61] Although neuroimaging has enabled visualization of structures for both diagnosis and surgical treatment, radiographs, CT, and MRI have typically been limited to 2D or a volumetric representation in 2D slices.[62] There have evolved various computer software programs that can take 2D information drawn from the aforementioned DICOM sources and reconstruct them in a volumetric fashion.[63] Several studies have suggested that incorporation of such 3D imaging of anatomical structures may help students and residents learn and retain relevant information in a shorter period—an idea that has undergirded the proliferation of medical volumetric modeling.[58-62,64]

Although VMs are an immersive and unique way to expose learners to large swathes of human anatomy, virtually all existing DICOMs techniques to create these models involve either some or all these issues: 1) low quality of corridors reconstruction, 2) lack of texture, or 3) extensive data collection.

Techniques to Create Volumetric Models

As previously mentioned, models created from DICOM files—by their derivation from CT/MRI scans—necessarily abstract away relevant textures and are unable to meaningfully recreate corridors and minute structures. Nevertheless, specific structures such as fiber tracts can be easily generated with good results using DICOM. Indeed, for the creation of this atlas, we have incorporated models from fiber tracts to increase the understanding of the white matter of the brain. We still believe that at this moment, DICOMs reconstructions for fiber tracts are

one of the best resources to truly understand the disposition and shape of different tracts. We think that DSI studio is a great tool to perform virtual fiber tract dissections both as a standalone resource and in combination with brain white matter dissections.

The SLS method—which uses a specialized light scanner to capture the target image—is moderately better at recreating narrow spaces and achieving adequate texturization. Nonetheless, it is a surface scanning technique that requires extensive data collection and typically does not have the portability to be used in dynamic and tight spaces. The PGM method has higher portability and yields optimal texture quality—which in turn improves anatomical fidelity.[65-66] However, like SLS, it is essentially a surface-capture technique and is typically unable to adequately capture narrow spaces and corridors. PGM and SLS require a computer with high GPU and CPU performance. This may be very expensive and time-consuming; for these reasons, new techniques for VM reconstructions from photos or scans have been developed. The cloud-based PGM platforms allow to upload photos directly from your phone and create VMs with an automatic workflow. This is a fast, low cost and simple alternative to PGM and SLS. Nevertheless, these platforms create VMs with lower resolution compared with standard PGM and SLS. Moreover, these platforms use an automated workflow that don't allow post-processing during the model creation, which leads to more defects in the mesh. Models of neurosurgical anatomy are particularly complex since the small and intricate details of the nervous structures. Therefore, low-quality (and, frequently, low-budget) options should be considered only for reconstructions of superficial layers or with fewer details.

Lastly, 3D models can be generated using 3D modeling software. This requires the expertise of a 3D artist, which can be time-consuming and expensive. Nowadays, several platforms with common creative license material models can be downloaded for free when used for education. We believe that these models are very helpful for a schematic understanding of neuroanatomy.

Though, they cannot compare to SLS or PGM reconstructions in terms of resolution, texture quality, and realism.

Photogrammetry vs Structured Light Scanner

Both SLS and PGM have specific advantages and limitations. The best commercial 3D scanners have a reported accuracy of ≤30 µm, a nominal resolution of ≤100 µm, and a rate point accuracy of ≤50 µm.[65-68] Thus, these scanners will be most effective when digitizing small-sized objects with intricate details and sharp edges, such as certain neuroanatomical specimens. These scanners can generate 3D models with an accuracy of up to ~100 µm.[52] Although SLS setups have typically been more expensive compared with PGM, the physical sensors on SLS scanners allow for the reconstruction of the meatus, foramina, canals, and other anatomical corridors. In contrast, PGM lacks the reflection of visible light from the deeper structures, which results in the construction of black meshes.

PGM-textured models seem to have improved texture quality and, thus, greater cosmetic precision compared with those generated by SLS, which might improve anatomical fidelity. In judging whether PGM is an appropriate tool for generating neuroanatomical reconstructions for a given project, several practical considerations must be contemplated. The primary benefits of PGM technology include portability, greater texture quality, and lower costs. However, the primary drawback of PGM is imaging capture. Taking photographs with a DSLR camera of a single specimen can be accomplished in ~30 minutes and taking a video can require 5-10 minutes. If more surface of the specimens needs to be acquired, the time for imaging capture can increase up to 60 minutes. In contrast, scanning the specimen via SLS will require ~15-20 minutes. Time of imaging capture can decrease to ~15-20 minutes when using a smartphone or an endoscope since there is less set-up requirement (e.g., positioning the specimen in the turn table, light flash setup) and the camera moves around the object or point of interest.

Nevertheless, the quality of the model reconstruction, such as mesh details and texture, are lower than the standard camera. Although imaging capture may be time-consuming, PGM hardware is highly portable. Given an adequate light source, the only equipment needed to collect photographic data is a DSLR camera or smartphone, a tripod (optional), and adequate flash card storage capacity. Neither a computer nor electrical power is required on-site unless plug-in lighting is used. Such portability advantages make PGM useful for data collection in the operating room or at a dissection station distant from a main power source or computer because photographs can be taken for future remote digital reconstruction. In contrast, SLS always requires a powerful computer to save the scans and, therefore, is not easily movable from its workstation.

The tradeoff for the flexibility of data collection with PGM is that the processing after image capture is time intensive. For SLS, standard processing requires ~15 minutes (interactive). For PGM, manual correction of photographic masks averages ~1 minute per image. The suite of PGM model-building operations (alignment, geometry, and texture) is demanding of both RAM and video card, commanding >10 GB of memory at peak. The time required to complete these operations depends on the processing capability of the investigator's computer and the number of photographs used to build the model (Table 4).

Graphics issues in PGM include forming and decimating triangle meshes, merging multiple range images, and detecting scan artifacts. One issue with SLS is that cannot reconstruct deep cavities (such as the endonasal corridor) owing to the lack of physical sensors, resulting in gaps in the point cloud. Radial basis function interpolation or Delaunay triangulation can be used to patch over such holes.[69] Furthermore, edge curl will produce artifacts at sharp corners, permitting discontinuities in the computed mesh to arise. Surface scanning limitations with both techniques are related to surface reflectance and color, the translucence or transparency of surfaces, and speckle (constructive and destructive interference of light due to the

microstructure of the reflecting surface, although this will not usually be a problem). The substantial flexibility offered to the investigator in photographing a specimen suggests that different protocols could create variances in model quality.

Learning the workflow of PGM is more intuitive than SLS. Users with photography skills have an advantage in imaging capture and pre-processing. For the processing step, the learning curve is straightforward for programs with an automatic roadmap, such as RealityCapture. Besides, there are plenty of educational resources for PGM, due to the popularity of this technique. On the other hand, the SLS workflow is less intuitive and with fewer resources to learn from. Furthermore, for neurosurgical models, with several tiny structures and high details (e.g., shape, texture), it is necessary to use a scanner with high resolution to obtain a good reconstruction, therefore options are more limited.

In terms of costs, as listed in Tables 2 and 3 is clear that PGM is cheaper than SLS. However, to acquire the highest material and programs, the PGM workflow can be quite expensive too. Something that should be mentioned is that several software have discounts for educational propose. For example, Capture Reality and Substance painter give free licenses to teachers. In the low-budget columns for PGM and SLS, we have listed some of the available materials to perform the two techniques at a lower price in exchange for the lower quality of the reconstruction. Nonetheless, these are good options for someone that wants to try different techniques before spending the amount needed.

Since SLS is superior for resolution and allows reconstructions of tiny structures, and PGM is superior for texture quality, we have generated VMs combining these two methods (See Bones collections). In our opinion, the combination of these two techniques yields the highest-resolution models in terms of mesh details and texture. Disadvantages are the need for the full equipment for SLS and PGM, which leads to cost, and time increase due to the combination of the workflows and the processing for alignment of the different meshes.

Post-processing and Rendering

Post-processing of the models is a key step to enhance the result of the reconstruction. Indeed, in our workflow PGM and SLS, this step has been integrated into different phases of the VM creation. The first post-processing stage is after mesh reconstruction. Once the mesh has been decimated (500.000-1.000.000 polygons), we usually export it from the PGM/SLS software and import it into a 3D modeling software, regarding the complexity of the model and the result of the first reconstruction. Here the mesh is smoothed, holes closed, and reconstructed when needed. For example, it is very common that nerves or small arteries can be unproperly reconstructed especially using PGM. After improving the mesh quality, the new object can be imported back into the PGM or SLS processing software, and texture can be generated. We suggest doing mesh post-processing before the texture generator to avoid mismatch. Once the model is fully created, texture post-processing is another crucial step that will improve the quality of the model. Importing the model and the texture to Substance painter allow the user to improve the overall quality of the texture (e.g., exposure, shadows, levels, saturation), but also to use the clone stamping or painting tool for black holes, undesired parts, or spots with imperfection in the specimen (e.g., arteries not properly injected, discolored skin parts). A specific region of interest can be highlighted with different colors or changing light exposure. Furthermore, labels can be added directly to the object to increase understanding of the anatomical structures (see Craniometric points collection). Although post-processing is, in our opinion, a crucial step to increase the quality of the models, it is time-consuming and requires expertise in computer graphics.

Model rendering, on the other hand, is not necessary to increase the quality of the models but to exploit their use. Rendering of a VM is a way of using the same object for several propose. For example, renders or pictures of the same model from different angles can be generated at any time. Also, animated renders are a great resource for implementing VMs in presentations

and publications. Another useful tool is combining two or more models, either contiguous structure (e.g., sphenoid, and palatine bone) or two layers of the dissection (e.g., DTI fiber tract, and brain model). This process will help the user to increase the understanding of the anatomy and the 3D disposition of the structures.

Virtual atlas of neuroanatomy and neurosurgery

The application of 3D computer graphics to neurosurgery has shown great promise. The advantage of VMs is that they allow 3D visualization and understanding without needing another tool rather than a smartphone or a computer. VM models allow the exploration of dissected structures not only in a standard 2D perspective but in a 360º stereoscopic view of the object. Surface reconstruction through 3D scanning techniques provides excellent color and texture feedback, which more accurately replicates the surgical anatomy emphasized by the dissection. The interactive experience of neuroanatomy and neurosurgery that 3D modeling can offer is enhanced through its encounter with 3D platforms. Sketchfab is a free platform that is easily accessible and where users can visualize and interact with the VM in 2D, AR, and VR. This enhances the understanding of the anatomy and makes this atlas available at any time. This novel virtual atlas of neurosurgical anatomy is a free and always-in-expansion tool that has several applications. Medical students and neuroscientists with a particular interest in neuroanatomy can have an innovative tool to learn and teach brain and spine anatomy. Neurosurgical residents and attendings can interact with VMs of several intracranial and spinal approaches and review the microsurgical anatomy and all the steps of each procedure. This could play a crucial role in decision-making and surgical planning and may support patients in understanding different aspects of their pathologies and therapeutic options.

In our opinion, any fellow that has the opportunity to spend time in an anatomy laboratory should recreate VM of his/her dissections. Indeed, creating a VM from an anatomical

dissection is a way for the author to improve the understanding of anatomy and to exploit the use of a laboratory. Additionally, one single model can be a resource that can be used in time for different renders and animations. The different steps for VM reconstruction (especially post-processing and rendering) require a high level of knowledge of anatomy and should be considered as another learning tool not only for the viewer but also for the author.

VMs from cadaveric dissections are also a way to virtually plastinate the specimens. When the dissection is finished and the donor returned, we can go back to the virtual reconstruction and continue to learn and review the anatomic variations that were found. These donations are a precious resource for learning, not due to the logistical difficulty of finding donors, but because they were people, and they are our teachers in the laboratory. The VM reconstructions are another way to preserve them and to honor their wishes, now in the virtual space.

Future Directions

Relatively new technologies such as VR, AR, and mixed reality can enhance the interactive experience of VMs, and one day may provide a unique avenue for surgical planning and immersive surgical simulation. Virtual reality systems with built-in haptic feedback have been developed, and systems that accurately replicate patient-specific features are currently in early development.[67] All such innovations are crucial given the complexities associated with the neurosurgical field, along with the learning curves associated with the different surgical skills.[68] An additional platform that may serve as a unique display for VMs is the light-field display, which soon could allow us to interact with holographic representations of still or animated volumetric models. Lastly, new pedagogical methodologies are in the process of being investigated—to assess the role VMs will play in educating the next generation of physicians.[60,69,70] Virtual surgical simulation platforms are the next step for exploiting VMs. Ideally, the user would be able to interact with the model in a surgical setup (e.g., microscopic,

endoscopic view). This will lead to an increase in the understanding of neurosurgical anatomy, reduce the learning curve for neurosurgical procedures, and provide better clinical outcomes. Three of our models are currently being used by an external University to develop a virtual reality surgical simulation application.

Lastly, the newest technological advancement inn programming and photography, will lead to the design of a reconstruction software based on artificial intelligence that will be able to recreate realistic VMs with high details, lower cost, and processing time.

Conclusion

The application of 3D computer graphics to neurosurgical education has shown great promise and has become increasingly prevalent in the reported data because development in other fields has facilitated its use in medicine. VMs are an innovative and immersive method to experience the intricacies of neuroanatomy and will likely continue to proliferate in academia and popular culture in the future. The present study has described 2 of the most common methods for producing a volumetric reconstruction of anatomical models: surface capture via PGM and SLS. Given the variety of workflows, it is feasible for neurosurgeons and anatomists to use the necessary hardware and software and generate high-quality in situ VMs for neuroanatomical education, surgical simulation, and surgical planning. SLS is preferable if high accuracy is desired and the imaging of anatomical corridors (e.g., foramina, meatus, canals) is required. PGM yields a viable alternative to dedicated scanners, with the potential to significantly broaden the accessibility of 3D research projects to academic institutions.

The virtual atlas presented here will be a great tool for residents and young neurosurgeons to have a full comprehension of the 3D disposition of the neurovascular structures and the different steps of the different neurosurgical approaches. The success in terms of visualization and citations of our publications are already indicative of the appreciation of these collections by the neurosurgical community.This is the first surgical virtual atlas of cadaveric dissections that has been described. We hope that could be of great interest and use for the future generations of neurosurgeons and that could inspire other authors both in neurosurgery or any other medical field to recreate similar database of VMs to support learning and teaching of the anatomy worldwide.

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