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3D Stereoscopic View in Neurosurgical Anatomy: Compilation of Basic Methods

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■ BACKGROUND: **Stereoscopy has been demonstrated to be a useful method of education in the field of anatomy because it allows users to see, in a simulation, the anatomical structures in their actual volume and depth.**

■ METHODS: **Cadaveric specimens preserved under formaldehyde using the Thiel and Klinger techniques have been dissected and photographed in the medical school anatomy laboratory (University Miguel Hernández) for the past 10 years. The photographic material and technique required to capture and project stereoscopic photographs have been described in different fields of surgical neuroanatomy. We used the results from a survey completed by the participants of different training courses to evaluate the utility of the 3-dimensional (3D) method.**

■ RESULTS: **A large database of photographs taken of different anatomical regions and approaches of neurosurgical interest was obtained. We have presented some examples in the form of pairs of photographs in 2-dimensional (2D) format, with explanatory labels, paired with the corresponding 3D photograph in anaglyph format. The survey showed that the lectures that had included 3D photographs were significantly better accepted than the lectures with conventional 2D photographs.**

■ CONCLUSIONS: **The teaching of basic, academic, and clinical neuroanatomy through the projection of stereoscopic photographs can be useful. The methods of image capture and stereoscopic projection in neuroanatomy, once combined with the necessary theoretical and practical knowledge, can be reproduced at other centers of neuroanatomy teaching.**

INTRODUCTION

We live in a 3-dimensional (3D) world. All the objects we see have a depth and maintain the distance from each other with respect to us. The organ of vision is based on the existence of 2 eyes. The images captured by the left eye are slightly different from those captured by the right owing to the distance between them. The images captured by each eye reach the visual cortex and are integrated into a single image.[1-3] This elementary principle in our daily life is termed stereoscopic vision.

When we consider neuroanatomy and its teaching, we must also consider methods that allow us to directly visualize the human body, specifically the central nervous system, including the dissection of cadavers, the use of synthetic models, observation of surgeries, and inspection of the human body. However, these methods will not always be available to all neuroanatomy students. As in any discipline of knowledge, the most affordable teaching material, in terms of availability and economic resources, is printed or projected graphic material. Obviously, the graphic material we have classically arranged for teaching has been produced in two dimensions. The reality of the nervous system understood as an interconnected spatial structure the surgical approach to which requires the use of deep anatomical pathways has led to the use of stereoscopy as a teaching method in neuroanatomy.[4-6]

In the present study, we had 2 main objectives. The first objective was to present our own methods of capture and projection in 3D stereoscopy applied to the field of neurosurgical

Key words
- 3D
- Neuroanatomy
- Stereoscopy

Abbreviations and Acronyms
2D: 2-Dimensional
3D: 3-Dimensional
EVA: Educational virtual anatomy
LED: Light emitting diode

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anatomy. In the "Methods" section, we have described our methods in great detail, and the "Results" section includes some examples of from huge database of photographs. The second objective was to summarize the history, development, and current status of this method of education in the field of neurosurgery. In addition, as a secondary objective, we attempted to evaluate the method using a simple survey that we have detailed later in our report.

METHODS

Basic Principles of Stereoscopy

Stereoscopy is the production of the illusion of depth in a photograph, movie, or other 2D image by the presentation of a slightly different image to each eye. The stereoscopic or 3D view results from the fusion obtained from both eyes. When we look at an object, 2 optical axes will be generated, 1 for each eye. For correct visualization of the object, 2 phenomena must occur: convergence and accommodation. Convergence is the intersection of the optical axes at a point. Accommodation is the optical focus of a point. Therefore, fusion would be the sum of both phenomena, and the stereo image would be the result of the fusion obtained by both eyes. Parallax is the angle formed by the direction of 2 visual lines relative to the observation of the same object from 2 different points, sufficiently far enough from each other and not aligned with it. This angle is essential for us to perceive the depth of objects and depends fundamentally on 2 factors (Figure 1).

Some factors must be considered when taking optimal 3D photographs:

1. *Optimal relationship of interocular distance/distance to the object ratio*

   The interocular distance/distance to the object ratio is ~1/30. If we place an anatomical specimen 60 cm from the camera to take 3D photographs, the distance between the 2 photographs taken would be ~2 cm. The closer the distance to the object, the shorter the distance between the photographs.
2. *Horizontal and vertical parallax*

   The only parallax that must be shown in stereoscopy is horizontal. In our normal binocular vision, everything is seen by 2 eyes located on the same horizontal plane in our face. However, when the shift between 2 images is produced on the vertical axis, the depth perception is uncomfortable.
3. *Similar images*

   The 2 images forming the stereoscopic vision must be similar in terms of light, contrast, and brightness and, of course, must show the same scene.
4. *Synchronized images*

   Both eyes must see the images of the stereoscopic pair at the same time.

Material

The Department of Anatomy of the Miguel Hernandez University has a long tradition in education and training in the field of neuroanatomy, collaborating every year with the Sociedad Española de Neurocirugía and other neurosurgical societies in the education of neurosurgeons from all over the world.

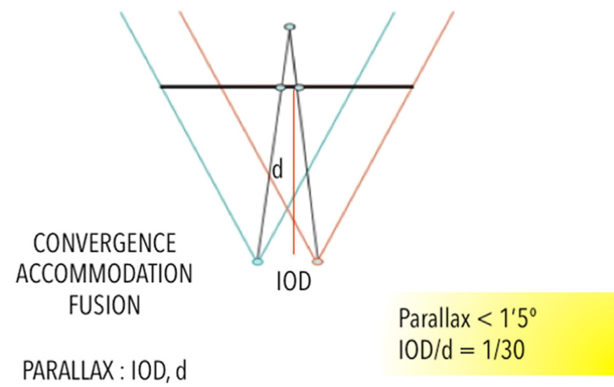

Figure 1. Concept of parallax. The interocular distance (IOD): the greater the distance, the greater the angle of parallelizing. The distance to the visualized object (d): the greater the distance, the lower the angle between the optical axes and, therefore, the lower the parallel.

The neuroanatomy laboratory is equipped with the following instruments:

1. Dissection
   - 2D conventional microscope (Zeiss OPMI PICO [Carl Zeiss, Oberkochen, Germany])
   - High-speed drill (Anspach EMAX 2 [DePuy Synthes, Raynham, Massachusetts, USA)
   - Endoscope, 0°, 4 mm (Karl Storz, Tuttlingen, Germany)
   - Basic instruments of dissection
   - Head holder
   - Two floor lamps
   - Suction devices and aspirators
2. Photographic material
   - 2D photographic camera: Olympus OM-D E-M10 (with the following objectives: 14–42-mm for basic and portrait zoom extra-low dispersion glass and 40–150-mm 1:4.0-5.6R for macrophotography.
   - Tripod: any photographic tripod can be used. The important point to acquire 3D photography is to have the capability to move the camera horizontally as accurately as possible between shots. Thus, a tripod with a built-in horizontal scroll bar can be used. A horizontal bar can also be incorporated into a conventional tripod, with a millimeter ruler to calculate the horizontal sliding distance needed.
   - Horizontal scroll bar of our own manufacture (Figure 2): the use of a tripod is suitable when taking remote photographs of isolated parts or anatomical regions well exposed to light and the camera lens. However, when seeking to photograph deep dissection fields without removing the anatomical

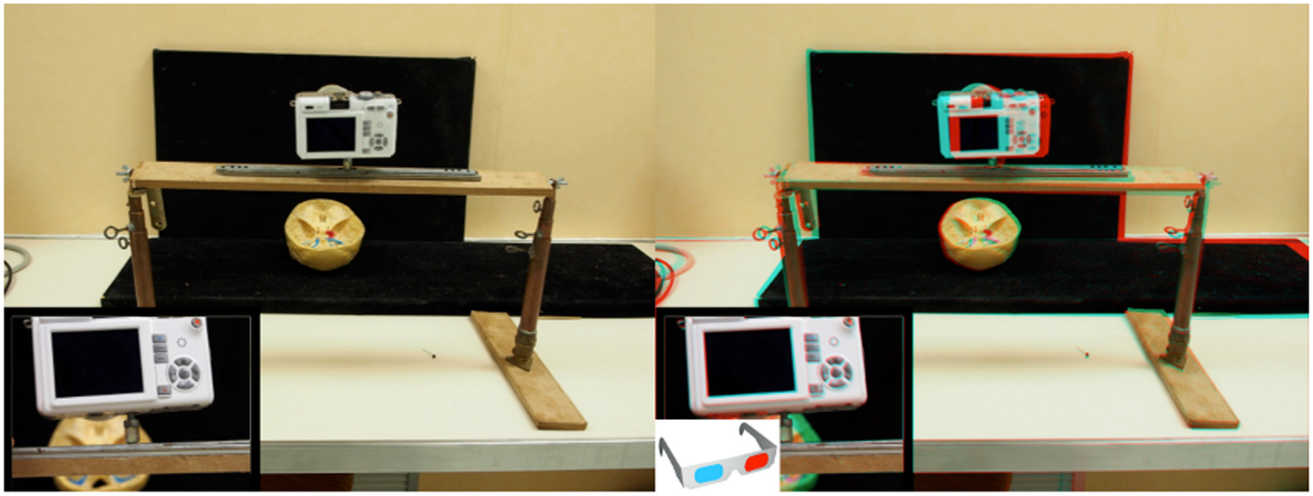

Figure 2. Our own manufactured "easy to move" horizontal bar. (**Left**) Two-dimensional. (**Right**) Three-dimensional.

specimen from the dissection table, the tripod will not be useful. The piece will usually be attached to the table with a cranial holder that is difficult to transfer. Thus, we manufactured a more versatile and easy-to-move device consisting of a rectangular wooden board about 3-cm wide and 18-cm long to which a sliding guide with aluminum balls and bearings was adapted. A screw such as that used by tripods to adjust and fix photographic cameras was inserted. The table is held on both sides by 2 legs, each made of aluminum bars of different diameters that would allow the height of the bar to be modified. Also, the horizontal bar can be adjusted with the legs such that the plane can be tilted and rotated $\leq 45^{\circ}$. With this lightweight and easy-to-transport device, we can easily photograph dissections without removing the piece from the work area.

- Microscope image capture device: to obtain photographs from our analog microscope, we use a device that allows us to capture the S-video signal that it emits (Elgato Video Capture [Elgato, Munich, Germany]).

3. Illumination

- The camera's own flash: the camera's own flash can be used to photograph a piece for which we wish to acquire a general plane and no deep areas are present that will generate shadows (e.g., a cerebral hemisphere or skull).
- Aputure Amaran LED (light emitting diode) ring flash universal mount, with adapter rings with 52, 55, 58, 62, 67, and 72-mm diameters to adjust the camera lenses (Aputure, Los Angeles, California, USA). This mount is especially useful for closer photographs. However, its use is not recommended if the field is very narrow and deep, because in such cases, the diameter of the flash will be very large, and shadows can appear after moving the camera horizontally during the stereoscopic process.
- MAL-1: a macro flash kit composed of two flexible "antennas" with LED lights, which fits the camera's flash slot. Although it seems very simple and rudimentary, in our experience, it has been the best lighting method for deep fields in which we need to introduce the lighting very precisely to not create shadows when lateral displacement of the camera occurs between the pair of photographs.
- Adaptable floor lamps

We performed our dissections and photographed different types of specimens, including the following:

- Dry skulls
- Formalin-fixed specimens with intravascular injection of colored (red/blue) silicon[7]
- Cadaveric specimens fixed using the Thiel technique, which is especially useful for soft tissues such as skin, muscles, and nasal mucosa[8]
- Brains fixed using the "freezing" technique, which exposes the white matter tracts developed by Josef Klingler[9] in 1931

Methods of Stereoscopic Photography

The technique used in the present study to take 3D photographs is based on simulating binocular human vision. Thus, we needed to take 2 photographs with a minimal shift between them, maintaining a perfect horizontal plane. Although it is a well-known practice, the objective of our study was to review the different technical details useful for the acquisition of stereoscopic photographs in the field of surgical neuroanatomy. To systematize the capture methods, we established 3 capture scenarios.

Isolated Anatomical Specimens. The technique required to photograph isolated anatomical pieces will not always be easy and can

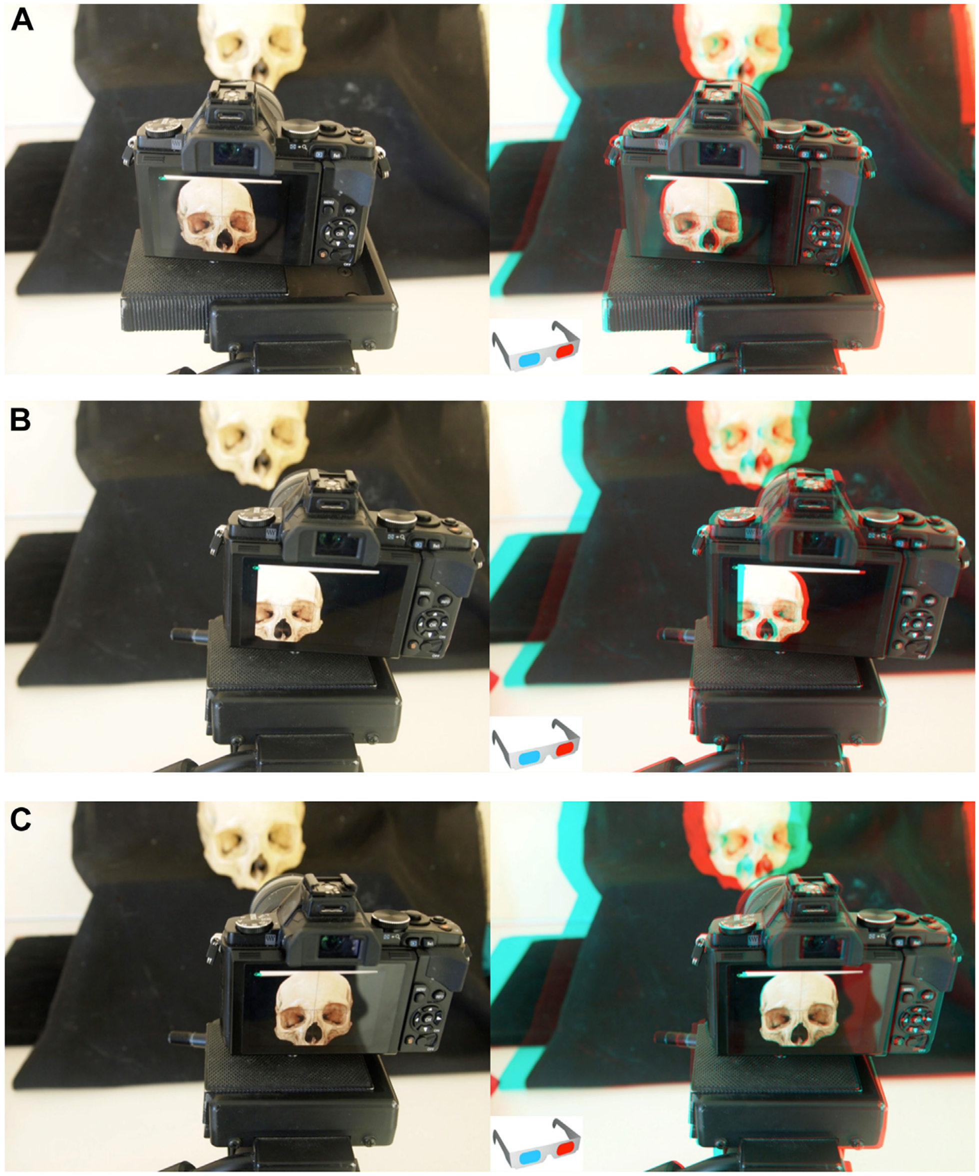

Figure 3. Process of stereoscopic capture with isolated specimens in front of a camera. We use a tripod with the camera placed on a horizontal bar and controlled shift between photographs is possible. (**A**) A photograph is taken, focusing on a point of the specimen. (**B**) The camera is moved horizontally to the right (the distance of shift depends on the distance of the specimen). (**C**) After this shift, the point, previously focused, will have moved. Thus, the camera must be turned to focus on the initial point again and then another photograph taken. (**Left**) Two-dimensional. (**Right**) Three-dimensional.

be especially challenging when deep surgical fields must be photographed (Figure 3). In such cases, the distance, focus, and light must be adapted.

Microsurgical Approaches. For microsurgical approaches, we attempt to photograph areas of the anatomical specimens that show a certain degree of depth. Such cases will occur mainly when neurosurgical approaches that have been previously dissected must be photographed (e.g., an image of the cerebellopontine angle after performing retrosigmoid craniotomy). For such photographs, the simplest method would be to automatically capture the image from a high-definition microscope in 3 dimensions, because the focus of the image and the lighting would be in optimal condition. However, these devices

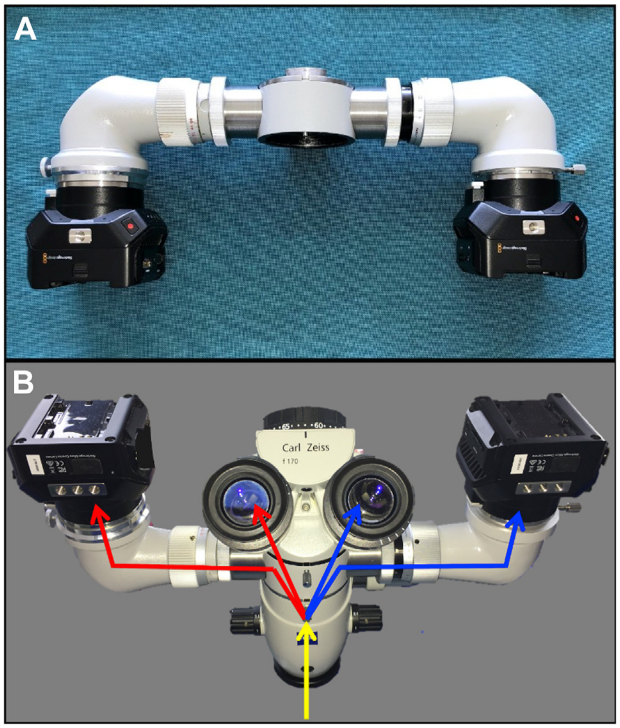

Figure 4. (**A**) The main components of the system for obtaining and recording 3-dimensional (3D) microsurgical videos. It is composed in the center by a Ziess 50T surgical microscope beam image splitter and laterally by 2 equal arms Zeiss F 137 adapted each to a Blackmagic Micro Cinema camera. (**B**) Microsurgical video recording system in 3 dimensions on the microscope. The *yellow arrow* represents the entrance of the image that reaches the image splitter, it is there that this image acquires 3 dimensionality when offered to the right and left eye from a different angle of vision. Thus, the vision from a left angle (*red arrows*), is recorded with the left camera, and the surgical video, observed with the right eye (*blue arrows*) is recorded with the right camera.

are too expensive to be available in conventional laboratories. We have used 2 methods to take photographs in these situations:

1. Using a 2D microscope:

   To use a 2F microscope, we need an analog—digital image capture device that allows us to photograph what we see through the microscope. The output of the microscope will always give us the image of one of the eyepieces, resulting in a 2D image. The head of the microscope is then moved on the horizontal plane to allow a pair of stereoscopic photographs to be taken.
2. Using cameras directly adapted to the oculars (Figure 4)

   Using 2 equal cameras and video adaptors in each beam splitter port allows one to obtain 2 images that are equivalent to the images received by both eyes of the surgeon. Using the video signal from both cameras allows one to process them to obtain a 3D stereoscopic recording. The setup was implemented on a Zeiss OPMI surgical microscope (Carl Zeiss) with a 50% beam splitter, 2 video adapters with a focal length of 125 mm, and 2 Blackmagic Micro Cinema cameras (Blackmagic Design, Pty, Ltd, Port Melbourne, Victoria, Australia).[10]
3. Using the camera and horizontal bar (Figure 5):

   Using the camera and horizontal bar consists of adapting the camera to our previously described manufactured capture system. The horizontal bar device is placed perpendicularly, with the line formed between the camera and the area to be photographed, and the pair of photographs are taken with the corresponding horizontal displacement of the camera on the bar. The lighting method used will depend on the depth of field.

Endoscopic Approaches. When 3D photographs are required of a dissection performed using an endoscopic technique, some technical difficulties could ensue (Figure 6). The endoscopic photographs we usually take are mainly related to endonasal approaches to the skull base. In this scenario, our camera will be the endoscope. The corridor in which the endoscope is placed is the nose, a narrow corridor in which the maneuverability of the camera is poor. As with previous scenarios, the capture technique is determined by making a minimum horizontal shift between the first and the second photograph. If we remember the 1/30 ratio in millimeters, because the distance to the structure to be captured in these cases ranges from ∼30 to 60 mm, the calculated displacement between the 2 photographs will be ∼2 mm. The main disadvantage of the technique is that the focus to a reference point necessary for each capture requires a rotation of the optics, which will not always be possible because the camera is trapped in a narrow field (i.e., the nose). Thus, the 2 photographs will be taken with a purely horizontal sliding of the endoscope without rotation. Although this simplifies the technique, the disadvantage is that the photographs have significant differences in their periphery. As discussed in the Introduction, this violates one of the rules of perfect stereoscopy. Although viewing the images can be somewhat more uncomfortable than with open field photography, the effect will be minimized when the viewer focuses on the center of the projected image.

Conventional surgical endoscopes, unlike microscopes, provide us with a 2D image. The perception of depth necessary in surgery is provided by the indirect mechanisms previously described in the Introduction. However, engineers are developing optics and cameras that collect a double image through the optics and will allow us to obtain the desired stereoscopic image.

Methods of Stereoscopy Projection

Once the pair of stereoscopic photographs has been taken, different methods are available to view them. These include cross pictures, anaglyph 3D, and the polarized method.

Cross Pictures. The simplest method is the use of cross pictures, which consist of 2 stereoscopic images located one next to the other. The left image is located on the right side, and the right image is located on the left. The user must cross their eyes to perceive a single image in the center of their field of vision. The

Figure 5. Our own horizontal bar to capture stereoscopic images. (**Left**) Two-dimensional. (**Right**) Three-dimensional.

advantage of this technique is that it does not require hardware and the original color of the photographs is maintained. However, to achieve correct visualization, training is required, and the effort of accommodation can be very uncomfortable.

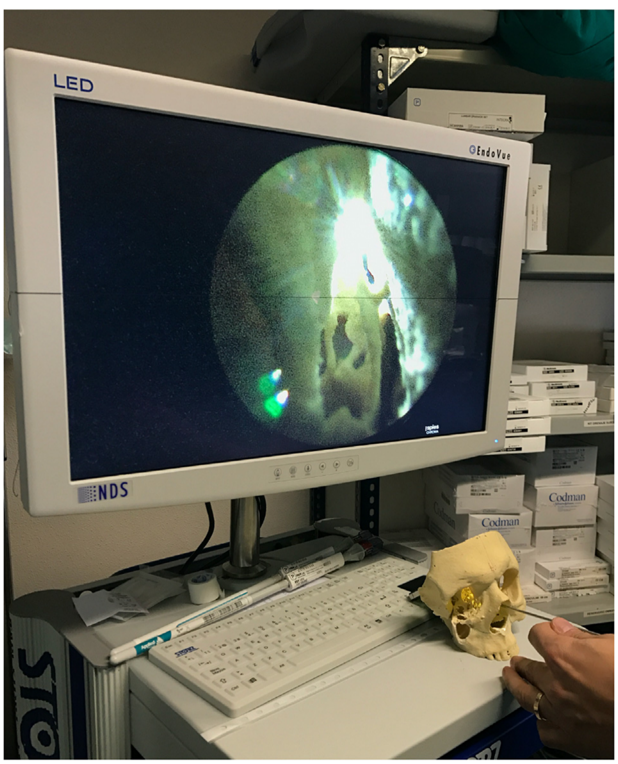

Figure 6. Endoscopic method of taking stereoscopic photographs.

Anaglyph 3D. Anaglyph 3D is the 3D effect that consists of encoding each eye's image using color filters, usually red and blue. The visual cortex of the brain fuses this into a single 3D image. The traditional method used to edit the images is very complex. However, at present, many software programs are available that will simplify the process. The main advantage of this technique is the ability to see the images in any format, including paper, any computer screen, and any conventional projection system without the use of filters (just blue—red glasses). The main disadvantage is that the color of the image created will not be real and causes discomfort after a long display.

Polarized Method. The polarized method is probably the most used method of 3D projection (Figure 7). The projection system is slightly complex. A slide presentation is created with 2 stereoscopic images located on each half of the slide (with the photograph corresponding to the right eye's vision on the right side of the slide and the photograph corresponding to the left eye's vision on the left). A special graphic card divides the laptop's screen into 2 halves, such that each stereoscopic photograph reaches its corresponding projector and is superimposed onto a special (silver) screen. Each projector has polarizing filters placed in front of its lens. The viewer wears low-cost glasses, which contain a pair of different polarizing filters. Each filter passes only the light that is similarly polarized and blocks the light polarized in the opposite direction; thus, each eye perceives a different image.

Compared with the anaglyph 3D method, this method allows for 3D viewing without altering the colors, although the brightness of the images will be slightly decreased. Another disadvantage is that it requires special projection devices and, thus, cannot be displayed on paper or using conventional projectors.

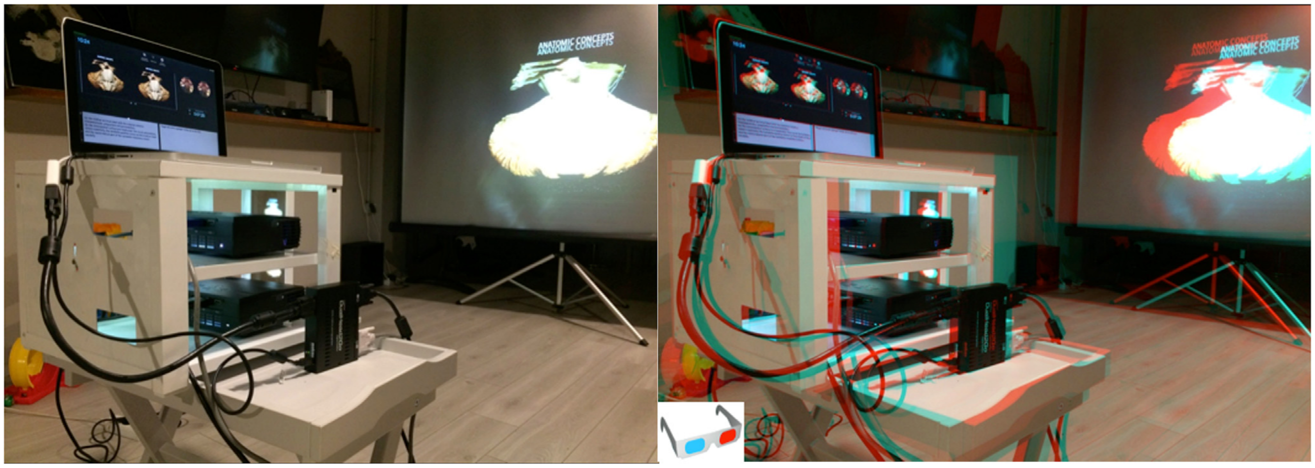

Figure 7. The projection system is slightly complex. A slide presentation is created with 2 stereoscopic images located on each half of the slide (the photograph corresponding to the right eye is on the right side of the slide and the photograph corresponding to the left eye is on the left side). A special graphic card divides the laptop's screen into 2 halves, such that each stereoscopic photograph reaches its corresponding projector and is superimposed onto a special screen (silver screen). Each projector has polarizing filters placed in front of its lens. The viewer wears low-cost glasses, which contain a pair of different polarizing filters. Each filter passes only that light that is similarly polarized and blocks the light polarized in the opposite direction; thus, each eye perceives a different image.

Evaluation of the Method

Evaluating a learning method is especially difficult and is even more so in the field of surgery because the ultimate goal of the method is to improve the trainee's knowledge of anatomy to improve the surgical results. Although this was not the main objective of our study, we attempted an evaluation of the learning methods used.

From 2013 to 2015, we coordinated the annual courses the Sociedad Española de Neurocirugía organized at the Miguel Hernandez University for residents focused on neuroanatomy and neurosurgical approaches. These are theoretical and practical courses that combine theoretical presentations and cadaver dissections and host ∼35 students annually. The lectures were projected in 2D or 3D format. After each course, a simple survey was completed by the students in which they scored the quality of the lectures from 0 to 10. To compare the mean scores of the 2D lectures against those of the 3D lectures, the Student t test was

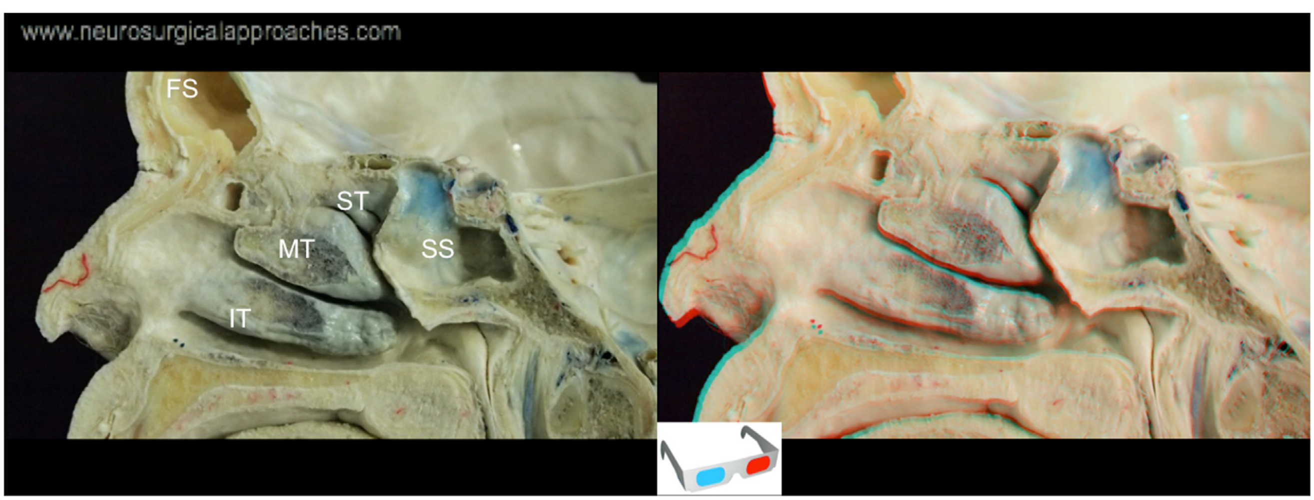

Figure 8. Anatomy of the lateral wall of the nasal cavity. (**Left**) Two-dimensional. (**Right**) Three-dimensional. FS, frontal sinus; IT, inferior turbinate; MT, middle turbinate; SS, sphenoid sinus; ST, superior turbinate.

used, and the level of statistical significance used in the hypothesis contrasts was $P < 0.05$.

RESULTS

The method of photography we have described has allowed us to collect a large database of 3D photographs (available at: neurosurgicalapproaches.com before 2014 and https://3dneuroanatomy.com/blog/ after 2014) related to neurosurgical anatomy and approaches. The atlas can be divided into different anatomical regions or scenarios:

- Nasal and skull base osteology (Figure 8)
- Craniometric points and relationship to the brain surface (Figure 9)
- Brain anatomy, including cortex and white matter (Figure 10)
- Anatomy of the ventricular system (Figure 11)
- Anatomy of the orbit (Figure 12)
- Endonasal transsphenoidal approach (Figure 13)
- Frontotemporal approaches (Figure 14)
- Anterior interhemispheric transcallosal approach (Figure 15)
- Retrosigmoid approach to the cerebellopontine angle (Figure 16)
- Infratentorial supracerebellar approach to the pineal gland (Figure 17)
- Surgical anatomy of the suprasellar region and cavernous sinus (Figure 18)
- Surgical anatomy of the spine (Figure 19)

Evaluation of the Method

Our analysis of the results of the survey revealed 2 points:

- The rate of 3D sessions required in these courses had progressively increased during the study period, from 22% in 2013 to 27% in 2014 and 64% in 2015.
- The mean score for the 3D lectures in all the courses was significantly higher than the mean score for the 2D lectures (Table 1).

DISCUSSION

Evolution of Neuroanatomy Education

Over the centuries, the history of neuroanatomy and its milestones has been attached to the teaching methods used. Like any science, neuroanatomy has multiple methods of education:

- Cadaveric dissection
- Plastination
- Observation of live models
- Live surgery
- Animal dissection
- Synthetic models
- Bibliographic sources
- Radiology
- Audiovisual virtual reality

The teaching of anatomy has perhaps the longest history of any field of medical education. Cadaveric dissection has

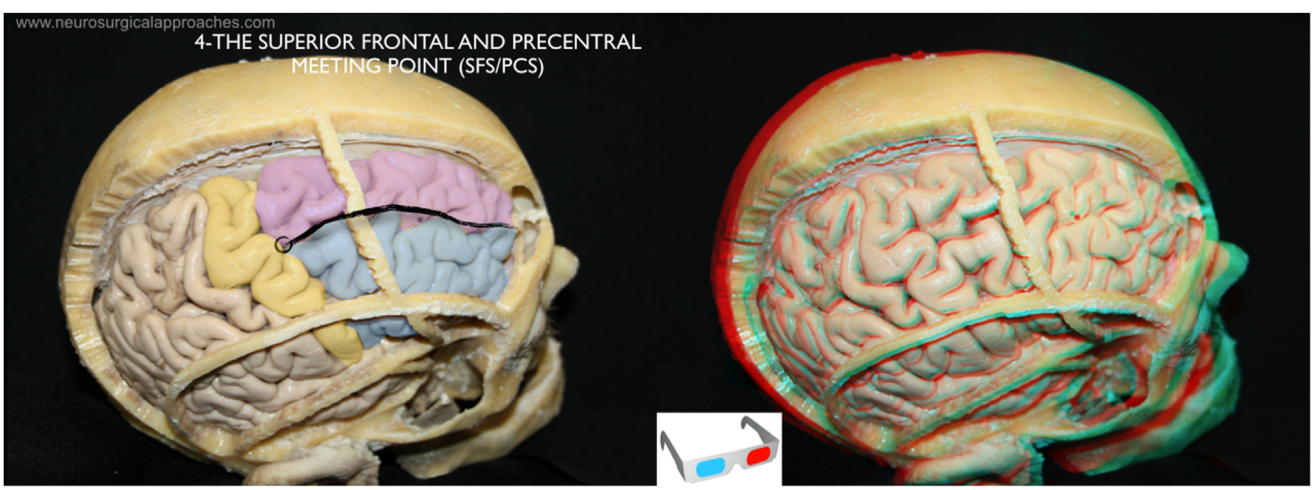

Figure 9. The superior frontal sulcus (SFS) and precentral sulcus (PCS) meeting point (*black circle*) and superior frontal sulcus (*black line*) is constant and usually a continuous segment and correlates with the underlying frontal ventricular horn. It is considered an important neurosurgical corridor. Previous to that intersection, the sulcus correlates with the hand motor activation area. (**Left**) Two-dimensional. (**Right**) Three-dimensional.

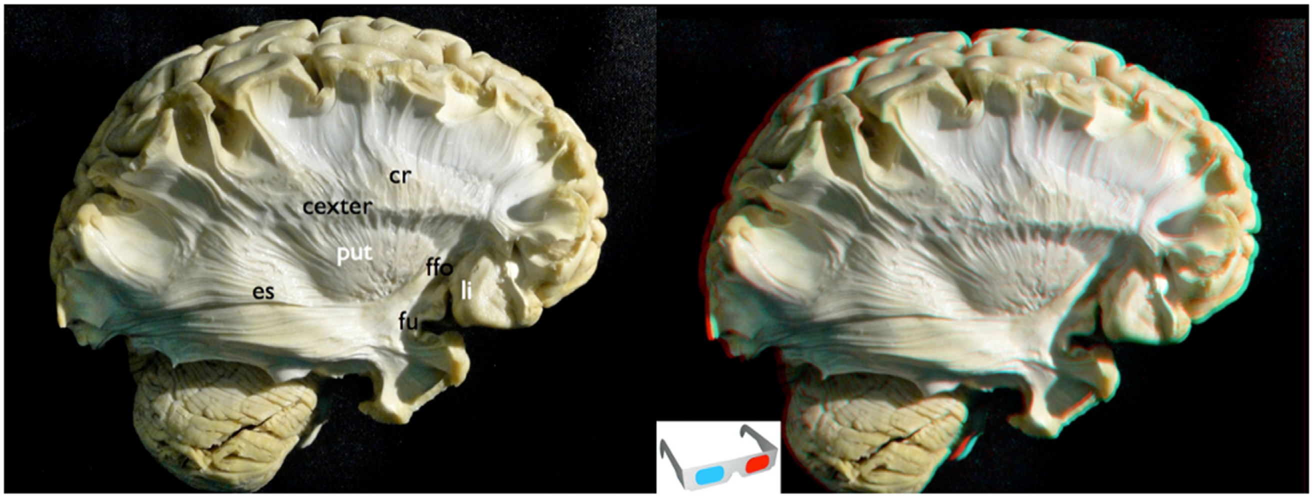

Figure 10. Dissection of the white matter at the level of the external capsule. (**Left**) Two-dimensional. (**Right**) Three-dimensional. cexter, external capsule; cr, corona radiata; es, estrato sagital; ffo, fronto-occipital fascicle; fu, uncinate fascicle; li, limen insulae; put, putamen.

probably been the most useful method for neuroanatomy research. However, the moral implications in managing a dead body have become controversial. Before the Middle Ages, human dissection was forbidden. Galen studied neuroanatomy by dissecting monkeys, and some investigators have reported that Herophilos was the first anatomist to perform a dissection on an actual human cadaver during the third century before Christ.[11] After the 13th century, Christian religion stopped considering the human body as something sacred, and Mondino de Liuzzi performed the first dissection in public. In the 16th century, Vesalius based his findings on human cadaver dissection.[12]

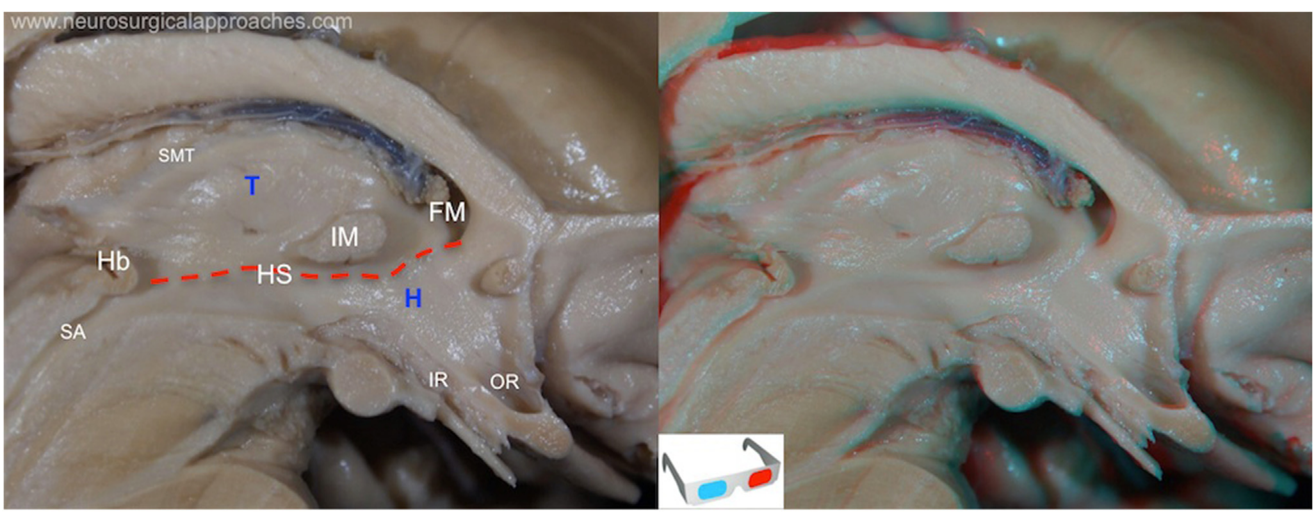

Figure 11. The lateral wall of the third ventricle, formed by the hypothalamus (H) inferiorly and thalamus (T) superiorly. They are separated by the hypothalamic groove, which is a depression that runs from the foramen of Monro to the Sylvian aqueduct (SA), passing below the interthalamic mass (IM). In a sagittal cut at the hypothalamic level, 2 recesses are exposed: the optic recess (OR) upward and the infundibular recess (IR) below. Also, at the superior thalamic limit, the thalamic stria medullaris (SMT) can be seen, which travels from the habenula (Hb) to the foramen of Monro, and is the fixing line of the tela choroidea inferior to the velum interpositum. The interthalamic mass consists of association fibers that connect both thalami and are present in 75% of the population. (**Left**) Two-dimensional. (**Right**) Three-dimensional.

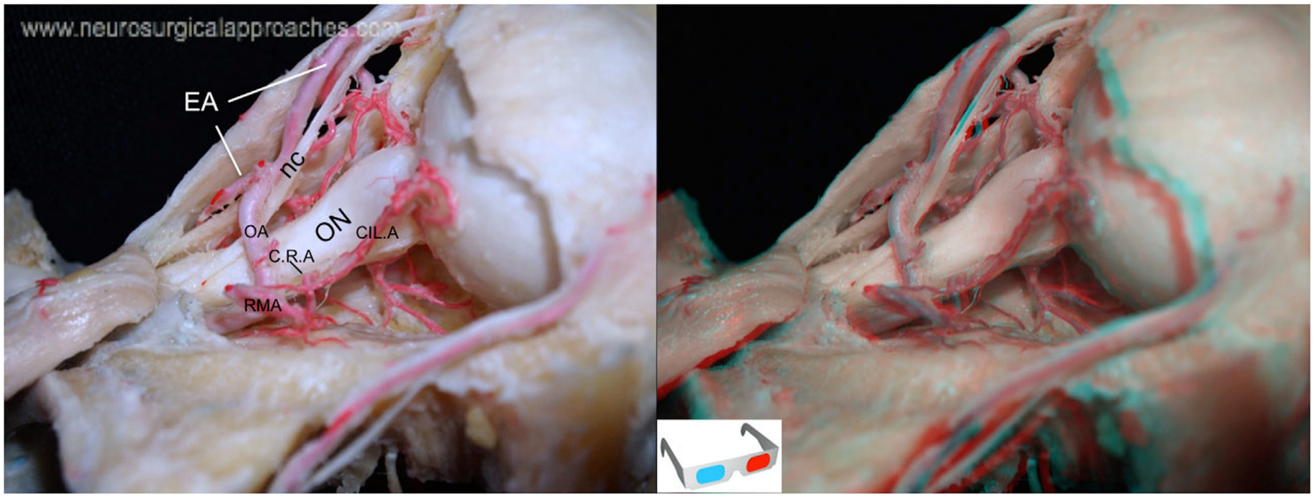

Figure 12. Superomedial view of the orbit. The anterior (AEA) and posterior (PEA) ethmoidal arteries are exposed, passing between the superior oblique and medial rectus muscles. The tendon of the superior oblique muscle (SOM) passes through the trochlea (T) and below the superior rectus muscle (SRM) to insert on the globe between the attachment of the superior and lateral rectus muscles. (**Left**) Two-dimensional. (**Right**) Three-dimensional. Front, frontalis nerve; OA, ophthalmic artery.

During the 18th century, many private medical schools expanded the use of a single specimen for a single student. However, only a few rich people had access to them. This situation stopped when public hospitals began to manage their own cadavers and dissection became available to all students. The old concept of an anatomy theater in which students could only watch the professor's dissection stopped, and the new trend became that every student started dissecting their own specimens. Most reports of anatomy teaching strongly recommend the use of cadaveric dissection.[13-16]

The 3 main benefits are as follows:

1. The appreciation of 3D relationships and anatomical variability
2. The development of fine motor control and a touch-mediated perception of anatomy

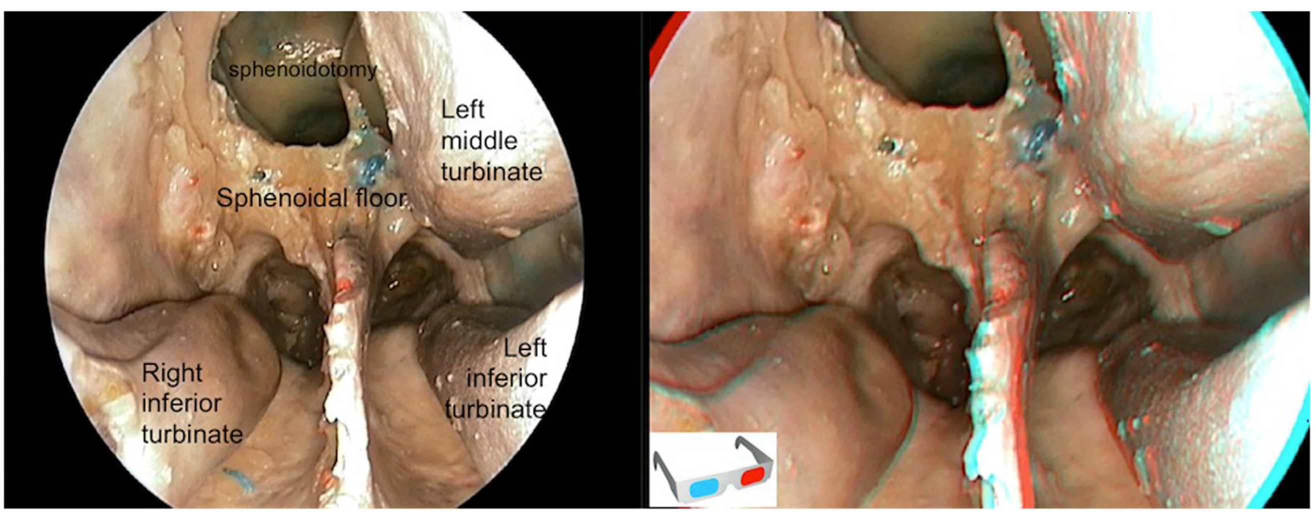

Figure 13. Nasal overview showing the right middle turbinectomy, resection of the posterior third of the septum, and sphenoidotomy. The nasoseptal flap has been removed to allow for better anatomical vision of both choana. (**Left**) Two-dimensional. (**Right**) Three-dimensional.

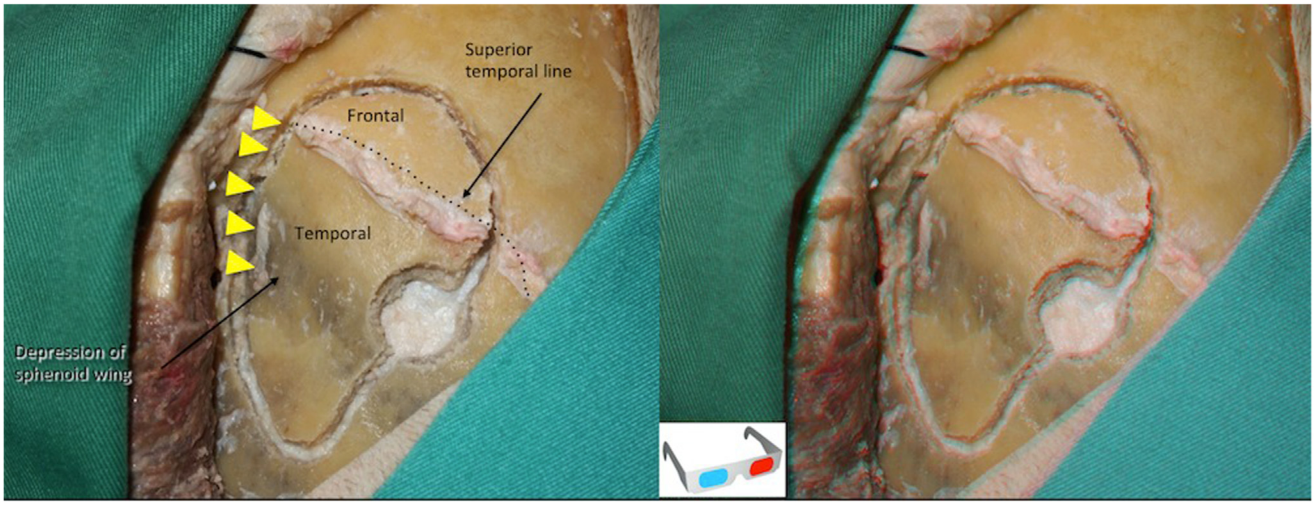

Figure 14. Lateral supraorbital approach. The craniotomy is performed with previous craniotome dissection of the dura from the inner table of the skull. The sphenoid ridge can sometimes be difficult to crossover with the craniotome, which can be solved by drilling a line over the sphenoid ridge with the blade (removing the footplate), lifting the bone flap, and fracturing the drilled line (*yellow arrows*). (**Left**) Two-dimensional. (**Right**) Three-dimensional.

3. The improvement of professionalism by direct contact with the cadaver, teamwork, and respect for the physical body

However, several important negative factors are also associated with studying anatomy through cadaver dissection:

1. The emotional impact: some studies have reported dissection to cause extreme anxiety and emotional problems for some students[17,18]
2. Health and safety problems secondary to exposure to embalming fluid chemicals or inadequately preserved human material and infectious diseases such as spongiform encephalopathies, human immunodeficiency virus, tuberculosis, and hepatitis[19]
3. Difficulties in acquiring cadavers; the costs of transporting, maintaining, and disposing of cadavers; the lack of qualified anatomists; and the large amount of time required for study by dissection

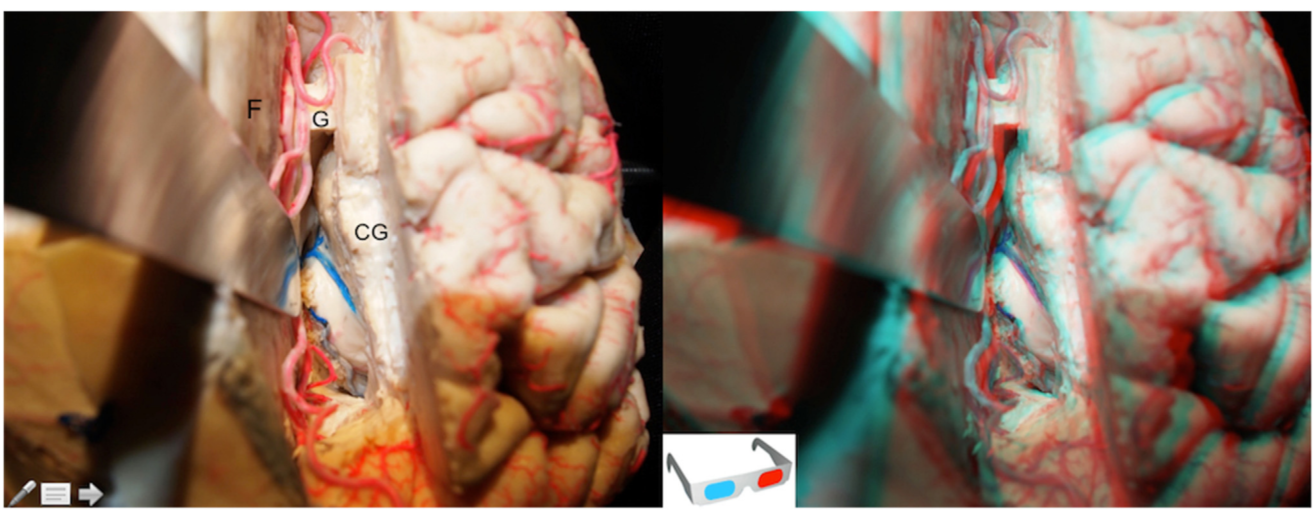

Figure 15. Anatomic overview of the anterior transcallosal approach. The retractor has been placed, simulating the surgical trajectory. Note the relationship between the genu of the corpus callosum and the foramen of Monro. (**Left**) Two-dimensional. (**Right**) Three-dimensional. CG, cingulated gyrus; F, falx; G, genu of the corpus callosum.

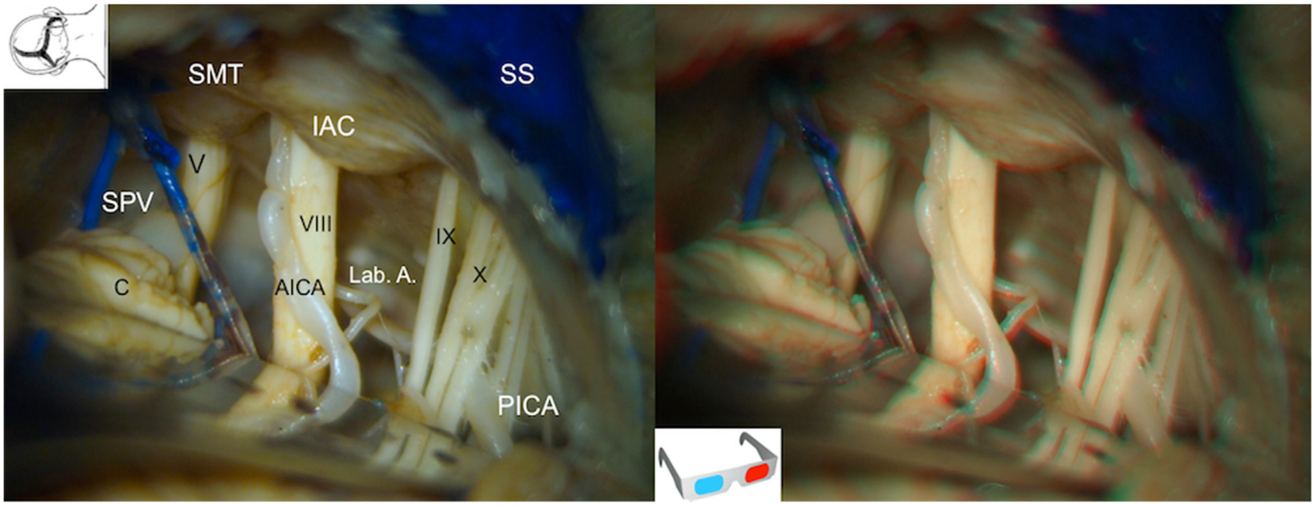

Figure 16. Microscopic view of the cerebellopontine angle from a retrosigmoid approach. (**Left**) Two-dimensional. (**Right**) Three-dimensional. AICA, anteroinferior cerebellar artery; C, cerebellum; CN, cochlear nerve (not visible from the right subclavian artery; anterior to the inferior vestibular nerve [IVN]); FN, facial nerve (not visible, anterior to the SVN); IAC, internal acoustic canal; Lab. A, labyrinthine artery; PICA, posteroinferior cerebellar artery; SMT, suprameatal tubercle; SPV, superior petrosal vein; SS, sigmoid sinus.

To adapt to the current changes in anatomy education, various complementary methods have been attempted. One of the most developed methods is processing radiological images using software. The digitalization of images has allowed for 3D reconstruction of any given anatomical region. All these methods of 3D reconstruction allow the user to perceive the anatomy in a real way. However, to have a greater perception of reality, the images must be visualized with 3D glasses or head-mounted displays.

The goal of the use of stereoscopy in neurosurgical anatomy is to mix both methods of education: cadaver dissection and virtual reality. Thus, we developed a project that includes anatomical dissection and its projection using 3D stereoscopic methods.

Evolution of Stereoscopy

Although the first official definition of stereoscopy dates from the 19th century, binocular vision has been studied previously by other investigators. Galeno was the first to describe the different visual

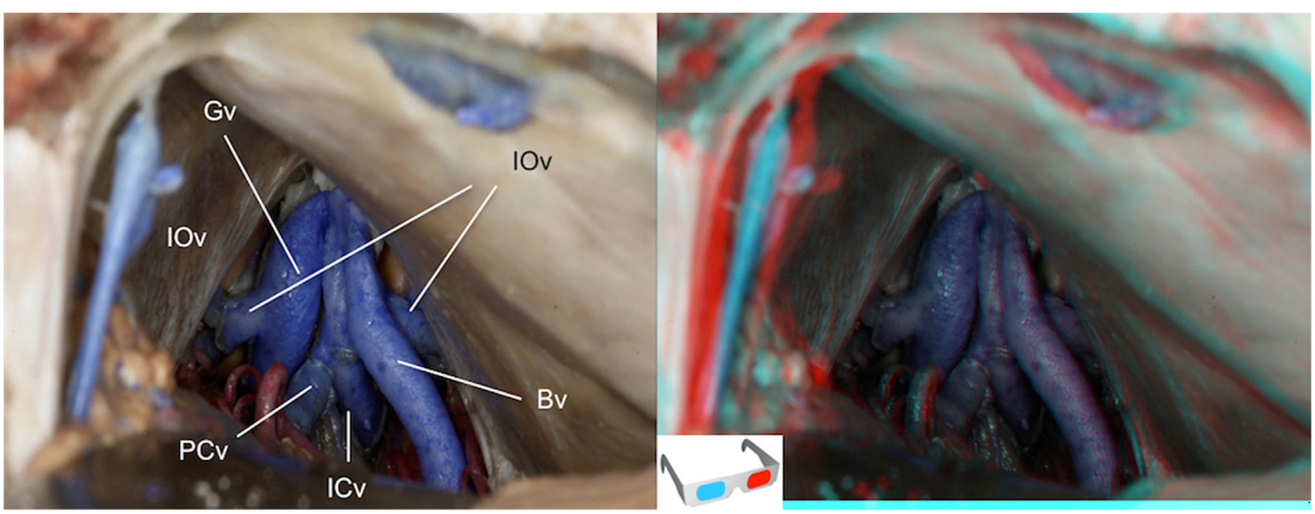

Figure 17. Microscopic view of the pineal region from a paramedian infratentorial supracerebellar approach. (**Left**) Two-dimensional. (**Right**) Three-dimensional. Bv, basal vein; Gv, vein of Galen; ICv, internal cerebral vein; IOv, internal occipital vein; PCv, precentral vein.

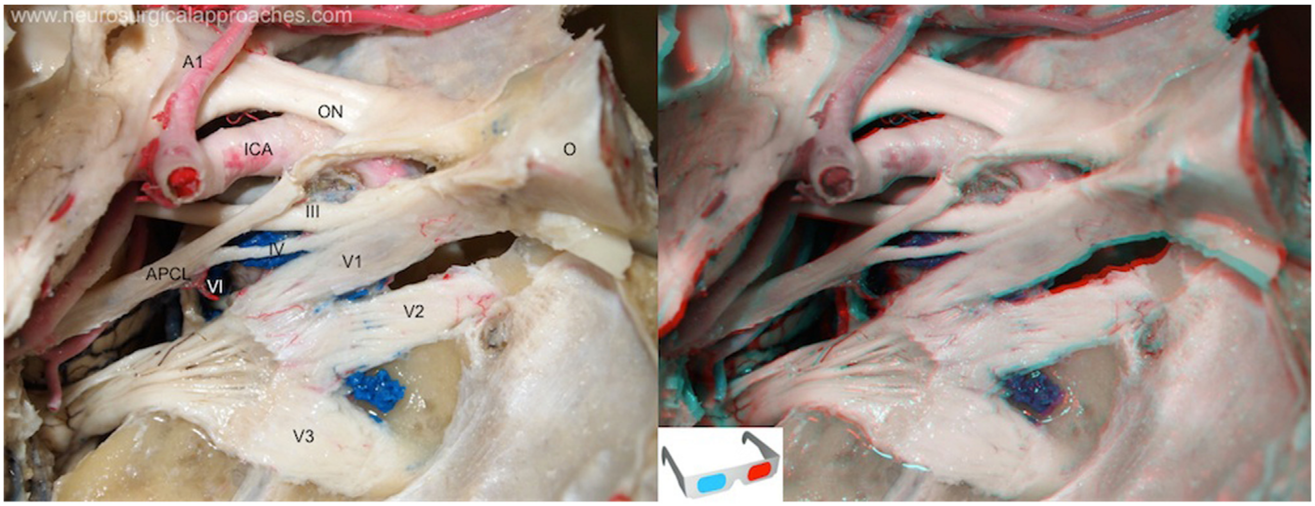

Figure 18. Lateral view of the right cavernous sinus with the main neurovascular structures dissected. (**Left**) Two-dimensional. (**Right**) Three-dimensional. APCL, anterior petroclinoid ligament; ICA, internal carotid artery; O, orbit; ON, optic nerve.

perspectives of both eyes. He considered that both eyes were seeing different images but that they merge in our brain as if they were only seeing one image. Leonardo da Vinci was the first to describe the rules of rectilinear perspective.[20]

In 1838, Sir Charles Wheatstone developed the first known stereoscopic device.[21] In addition, Daguerre introduced the first photographic camera known as the "daguerreotype." A few years later, David Brewster invented the so-called lenticular stereoscope, with placement of the lenses and mirrors in a closed box smaller than the Wheatstone device. One of the main factors contributing to the success of the invention was the interest that Queen Victoria of England had in stereoscopy.

In 1859, Oliver Wendell Holmes invented a simple stereoscope, which consisted of prismatic glasses in a wooden frame attached to a holder in which stereoscopic images were placed. It was probably the most widespread stereoscope ever used.[22-25] In 1858, Joseph d'Almeida and Louis Du Hauron (the inventor of color photography) made the first stereoscopic projections with the anaglyph.

During the second half of the 19th century, the birth of the cinema occurred. It was the beginning of the 3D movie. In addition, the use of stereoscopy as an educational tool began. An example is the publication in 1870 of a book by Hurst containing a large gallery of stereoscopic images of animals for teaching purposes. However, the first company to popularize the use of 3D images in education was Underwood & Keystone, which had collected thousands of stereoscopic images related to different subjects, including agriculture, geography, art, natural sciences, industry, architecture, science, or health.[26]

In 1939, at the Universal Exhibition of New York, a new stereoscope was displayed: the View-Master invented by William Gruber. This device was used to see cards of 7 pairs of stereoscopic photographs.[27] In 1962, David L. Basset (an anatomist), in collaboration with Gruber, published the first stereoscopic atlas of anatomy with >1000 photographs of anatomical dissections that could be seen with the View-Master.[28] In the 1950s, 2 events revived interest in stereoscopy. The first was 3D cinema. A tendency exists to think of B-rated movies when considering 3D cinema of that time.[29]

After the lack of technological improvements from the 1960s to the 1990s, a new revival of interest has ensued for the use of stereoscopy in academic and entertainment areas owing to the significant advances in imaging technology and computing fields. Since 2000, many movies have been filmed using 3D IMAX (image maximum; a format of high-definition video recording). The film director James Cameron popularized this instrument with the success of the film "Avatar" in 3 dimensions.[30]

In addition, the concept of virtual reality is key to understanding the current academic use of 3D images. Current virtual reality models are based on creating simulated environments through digital methods. The head-mounted display is a device similar to a helmet that the user wears and which projects the image directly onto the retina, increasing the perception of reality.

Benefits of Stereoscopic View in Neurosurgery

The objective measurement of the effectiveness of stereoscopy in the teaching of neuroanatomy is a utopia. However, the data provided by the surveys shown in Table 1 allowed us to demonstrate that a large group of neurosurgical trainees valued the 3D format positively in surgical neuroanatomy teaching compared with the classic 2D format. The main utility of stereoscopy in neuroanatomy teaching is the ability to enable a greater understanding of the spatial relationships and depth of the structures visualized. Because the reality around us is 3D, it is easy to understand that unless it is possible to place a real object in front of our eyes, the only method that will approach

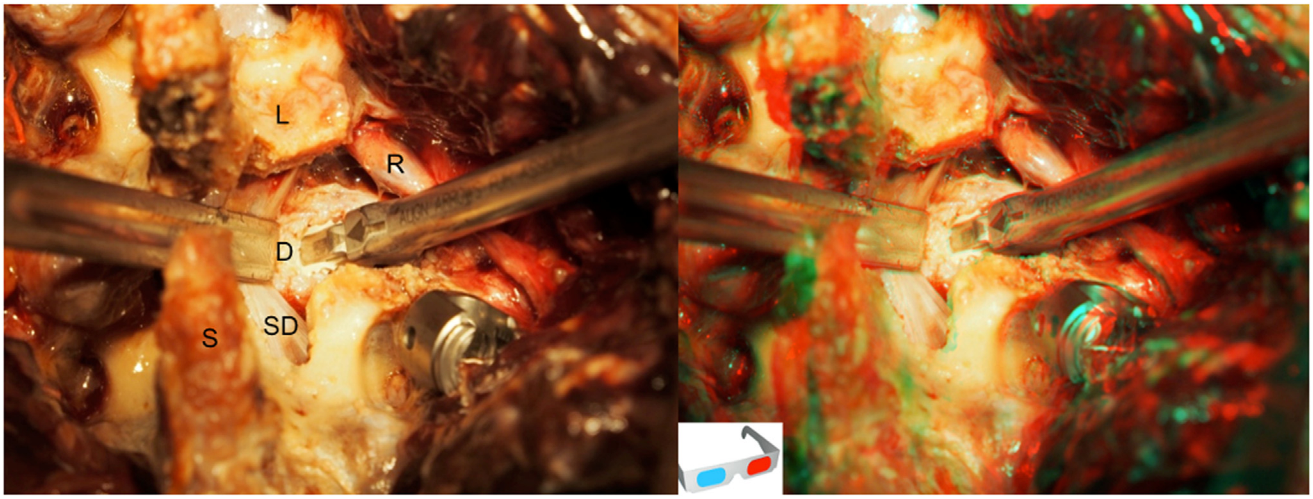

Figure 19. Anatomical view of transforaminal lumbar interbody fusion. In the right paravertebral region of the specimen, resection of the upper articular facet was performed, exposing the disc space and ipsilateral nerve root. After discectomy and medially separating the spinal cord, an intersomatic cage was inserted into the disc space. (**Left**) Two-dimensional. (**Right**) Three-dimensional. D, disc; L, lamina; R, nerve root; S, spinous process; SD, spinal cord dura mater.

reality when we try to view a representation of that object will be to project it in such that simulates its depth. The anatomy that neurosurgeons must learn must be as accurate as possible because they will need to know which structures are in a certain region. Surgeons will need to move through deep spaces where they must know the spatial relationships between the nerves, vessels, cerebral parenchyma, and/or skull.[31] The surgical microscope allows us to see in 3 dimensions. However, when we use an endoscope, most optics and cameras will project a 2D image. Therefore, with the use of endoscopy, it makes more sense to teach the depth of the anatomy before entering the operating room, because our perception of depth will be determined by indirect factors such as prior knowledge of the structures and their relative location. In our department, we performed 2 tests during surgery using different devices. The first was in 2012 with an endoscope marketed by Visionsense Corp. (Philadelphia, Pennsylvania, USA). The experience with the device was not entirely satisfactory because the wide field of view and the definition obtained were worse than those with conventional full high-definition 2D endoscopes. The second test was with the new TIPCAM S 3D ENT endoscope (Karl Storz).

Another advantage offered by stereoscopy is the ability to view a real image of the anatomy instead of using a cadaver, which avoids the inconveniences of cadaver use. These include the lack of availability, economic costs of the specimens and facilities for their use, discomfort of manipulating the toxic substances required to preserve the cadaver, and the psychological effects of facing a dead person.[32] Stereoscopy is useful, not only to represent photographs, but also benefits from the different virtual reality methods that can represent the anatomy such as 3D planning and reconstruction of radiological studies, virtual reality models, holograms, and so forth.[30]

Some investigators have evaluated the effects that stereoscopy has had in the teaching of neuroanatomy. One study was performed during application of the educational virtual anatomy (EVA) project. It was a computer program that provided medical students with a virtual reality tool based on radiological images of different regions of the human body in 3D volumes that could be manipulated by the students.[33] A survey was completed by 137 medical students at a university at which the EVA teaching method had been applied. Most of the students considered the EVA method to be better than anatomy books or master classes. Compared with cadaver dissection, 46% considered the value of the EVA project it to be similar or better than that of dissection. When assessing knowledge, a better result was obtained by the students who had used the EVA tool.[34]

Original Contribution of Our Study

The basic objective of our study was to review, in a single work, all the necessary techniques to create and project stereoscopy in the different areas of neurosurgical anatomy. Other investigators have reported on the usefulness of stereoscopy in the reconstruction of radiological images.[35-38] The novelty of our report was the step-by-step description of the materials and methods needed to acquire stereoscopic images from all fields of neurosurgical anatomy. Some investigators have described the techniques of 3D acquisition and projection, although most had used specimens exposed to a simple camera at a distance at which it is relatively simple to take stereoscopic photographs.[31-33] Few anatomical atlases or studies have been reported in the stereoscopic format. The need to use the anaglyph format has made their use not very widespread. A list of the most famous books follows:

1961, *The Stereoscopic Atlas of Human Anatomy*, by Bassett and Gruber

Table 1. Results of Surveys From Sociedad Española de Neurocirugía Courses, 2013—2015

Year, Course Title	Average Score: 2D Lectures	Average Score: 3D Lectures	*P* Value
2013, Anatomy and Surgical Strategies in Intracranial & Skull Base Endoscopic Surgery	8.33 ± 1.25 (n = 735)	9.16 ± 2.15 (n = 210)	<0.001
2014, Microsurgical Approaches to the Skull Base	8.49 ± 1.35 (n = 455)	9 ± 2.25 (n = 175)	<0.001
2015, The Cerebral Substance: Sulci, Gyri, Ventricles, and White Fibres Anatomy	8.4 ± 1.45 (n = 175)	9.39 ± 2.23 (n = 315)	<0.001

2D, 2-dimensional; 3D, 3-dimensional.

1985, *Stereo Atlas of Operative Microneurosurgery*, by Poletti and Ojemann

1994, *Microsurgical Anatomy of the Brain: A Stereo Atlas*, by Kraus

2003, *Cranial Anatomy and Surgical Approaches*, by Rhoton Jr

We also found some reports related to microsurgical anatomy.[31,39-41] However, we did not find any reports for 2 fields of surgical neuroanatomy: the endoscopic skull base approach and spine anatomy.

Endoscopic Skull Base. Most investigators of stereoscopy applied to endoscopy have explained their experience and results with the new 3D endoscopes.[42-49] Although the use of 3D in endoscopic surgery is not currently widespread, surgeons' knowledge should be developed with the help of the stereoscopy. However, 3D endoscopic endonasal anatomy publications beyond the one we reported in 2015 are lacking.[50] One of the reasons is that the method used to capture stereoscopic images with conventional endoscopes (not 3D endoscopes) is complex.

Spine Anatomy. To the best of our knowledge, our lectures of surgical anatomy at the 16th Congress of the Spanish Society of the Spine in 2016 represented the first use of 3D stereoscopy in this field.

Another singular contribution of our study has been the evaluation of the technique through the survey of course participants exposed to both 2D and 3D lectures. Although we did not have an analytical, but rather a descriptive, purpose, it is important to know whether 3D stereoscopy is a useful tool for neurosurgeons or medical students learning neuroanatomy. We are aware that measuring the usefulness of this technique is almost impossible because we are studying a method that will never be applied in isolation but always as a complement to traditional theoretical and graphic methods. However, the significantly superior evaluation of the 3D stereoscopic lectures by the participants has served as an objective element that validates our technique.

Limitations of Stereoscopy

Adverse effects associated with 3D vision have been reported. These effects can occur when the projected images do not meet the requirements described in our Methods section, including the disparity of appearance and the light of the stereoscopic images, poor synchronization of movement, vertical deviation, excess paralleling, anaglyph format, and so forth. When the images shown to the viewer are not appropriate, a conflict will occur in physiological convergence and accommodation.

However, pathological conditions exist that affect binocular vision, including refractive defects (i.e., myopia, astigmatism, farsightedness), strabismus, and amblyopia.[51] A poor perception of 3D images will lead to eye strain, pain, and disorientation. When viewing videos or movies in 3 dimensions, if the visual signal perceived does not correspond to the vestibular signals, it will cause dizziness and nausea. This phenomenon occurs more frequently in women because they have shown greater sensitivity in the visual—vestibular connection.[52] The binocular vision in children is acquired between 6 and 12 months of life. The full development of the eye is acquired at 3 years. From that age onward, it is considered that visualization of 3D content will not be harmful. In addition, 3D visualization has not been shown to increase the risk of epileptic seizures in patients with this pathology.[51] Several studies have suggest that ∼8% of the population will not be able to perceive 3D images. If we consider this problem, plus the proportion of people who experience discomfort when viewing 3D content, it could become an impediment to the popularization of this type of technology.[52]

CONCLUSIONS

3D perception in the field of surgery and, in particular, neurosurgery allows for an increase in the accuracy of procedures. Stereoscopy allows us to capture this reality from the operating room or dissection room for teaching using various visualization formats. Therefore, the projection of stereoscopic photographs and videos in basic, academic, and clinical neuroanatomy can be useful as a teaching method. This tool increases in value if used as a complement to other already validated methods.

The methods of stereoscopic capture and projection in neuroanatomy, once the necessary theoretical and practical knowledge has been acquired, can be reproduced in other neuroanatomy teaching centers. Further studies are needed to demonstrate, with objective data, the effectiveness of the technique in the teaching of neuroanatomy.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Javier Abarca-Olivas: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization, Project administration, Read and agreed to the published version of the manuscript. **Pablo González-López:** Conceptualization, Methodology, Investigation, Resources, Writing – original draft, Writing – review & editing, Read and agreed to the published version of the manuscript. **Victor Fernández-Cornejo:** Conceptualization, Methodology, Investigation, Resources, Read and agreed to the published version of the manuscript. **Iván Verdú-Martínez:** Methodology, Resources, Data curation, Read and agreed to the published version of the manuscript. **Carlos Martorell-Llobregat:** Methodology, Software, Resources, Read and agreed to the published version of the manuscript. **Matias Baldoncini:** Methodology, Resources, Read and agreed to the published version of the manuscript. **Alvaro Campero:** Methodology, Resources, Supervision, Read and agreed to the published version of the manuscript. **ISABIAL and University Miguel Hernandez:** Funding acquisition.

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