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Tesi di Dottorato

Nuove metodologie di studio dell'anatomia del sistema nervoso centrale in cadavere mediante tecniche di neuroimmagine, modelli computazionali e ricostruzioni tridimensionali. Sviluppo e future applicazioni per i principali approcci neurochirurgici

Dott. Matteo de Notaris

Ciclo XXIV

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A Maddalena ed Annamaria,
da dove è cominciato tutto.

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Objectives of the study

The goal of the present study was to develop a computer based three-dimensional (3D) anatomical and geometrical model of neurosurgical approaches. Such model can be employed for teaching surgical anatomy, developing surgical guidelines and provide for an advanced preoperative rehearsal system where surgeons try surgical procedure on a Computed Tomography (CT-scan) and Magnetic Resonance Imaging (MRI)-based imaging system.

Introduction

Background

The Surgical education has always been an exciting, challenging and dynamic discipline. It has a long history of innovative transformations that dramatically improved the way patients were treated and surgery was practiced. A variety of more or less formal educational practices have evolved over time. Indeed, the knowledge of surgical anatomy is imperative for complex surgical procedures in regions with vital structures nearby, as in neurosurgery.

Cadaveric dissection still remains the gold standard for training physicians in various surgical specialties as in skull base surgery. Until now, any computer simulation cannot substitute the study in the dissection room, for it is a unique experience that provides a wide range of sensorial inputs. During the dissection act, the surgeon progressively develops technical skills as well as acquiring dynamic view of the internal surface of the human body. Both knowledge and surgical technique comes from laboratory training [1]. However, limitations in acquiring and storing sufficient anatomical cadaveric material, legislative difficulties [2] and, on the other hand, progress in medical image processing techniques, has enabled to augment the surgical training in other directions. Actually, the field of surgical anatomy seemed to be in the process of reforming and modernizing itself. Simply describing and measuring anatomical details provides a general idea of anatomy, which is reflected in textbooks and atlases. But surgeons today have access to imaging techniques, which show them the individual anatomy of a given patient. Together with a profound understanding of the surgical anatomy, the combined use of sophisticated imaging techniques is the very basis of successful surgery [3]. It could be add that the study of the individual anatomy is the key point in the operating room as well as in the dissection laboratory.

The variability of gross anatomical structures within the human brain has been systematically measured and statistically analyzed by many authors in the last decades. Actually, what really makes the difference in the field of surgical anatomy is three-dimensional visualization, the morphology and the spatial relationships of the anatomical structures between them; is the possibility to augment the reality and the capability to accelerate the individual learning process.

Progress in computer technology and medical image processing techniques has enabled stereoscopic display of anatomical structures from computed imaging data [4-6]. Indeed, three-dimensional (3D) imaging, which allows image manipulation and surgical simulation on screen, has become an indispensable part of the neurosurgical training [7-13]. Recently, various efforts have been undertaken to improve surgical education and training. As interest in the development of technical skills training laboratories has grown in recent years, several investigators have worked to develop methods to objectively evaluate surgical skill and to improve the dissection techniques and instrumentation, mostly in the field of neurosurgery and skull base surgery.

Concerning white matter anatomy, during the last years excellent results have been achieved in improving the correlation between the traditional ex-vivo fiber dissection techniques and the diffusion tensor imaging (DTI) tractography in live patients [14-18]. However, less is known about the microanatomical validation of the main white matter fibers acquired by using the DTI technique in the same ex-vivo specimen. A specific part of the present 3D model, that we have named “Ex-Vivo Interactive Image Guided Dissection” aims to study the morphological characteristics and the course of the main brain white matter tracts by means of high-resolution magnetic resonance imaging (7 and 1,5 Tesla) and diffusion tensor imaging combined with microanatomical dissection of the same specimen. We have focus our research on developing a new method to investigate the human white matter and to assess the usefulness of the combination of both techniques.

In the present study we introduce a computer-based 3D anatomic model of different neurosurgical approaches and white matter dissection. Our method provided a detailed computer CT and MRI-based reconstruction using the pre- and post-operative data collected from different dissections in cadavers. Both types of models have been previously employed from recently published works of our group [19-23].

Methods

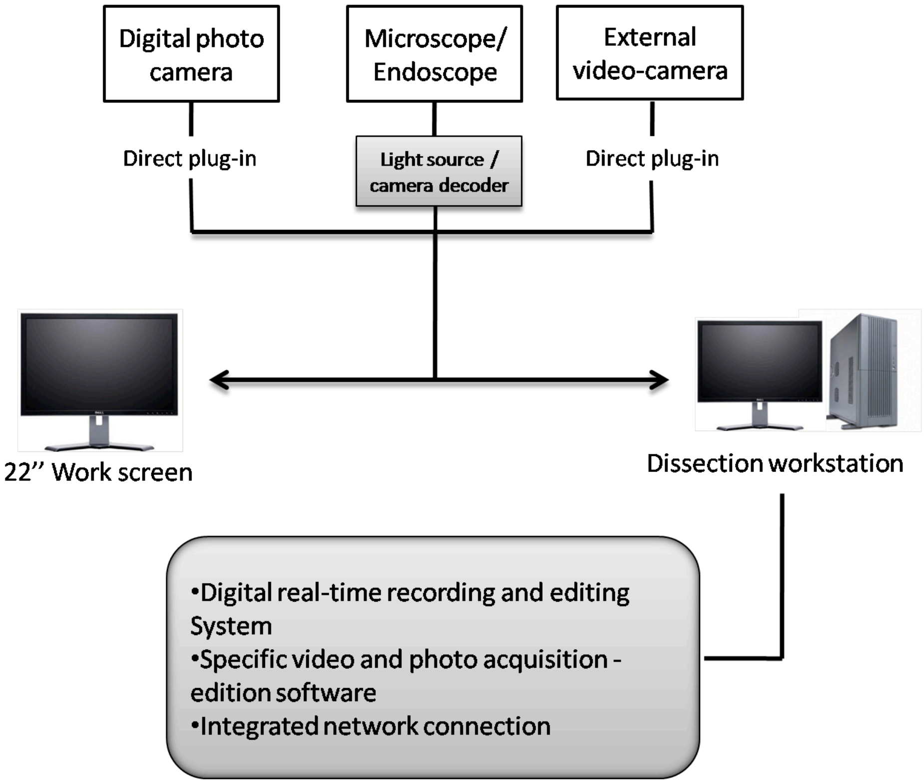
Thirty-four cadaver heads were dissected using the Cambridge fixation *formula* for skull base approaches and the Klingler[18] method for white matter approaches simulating the surgical position performed in the operating room, to achieve as much real surgical information as possible. For skull base approaches, only the arterial system was injected with red latex. Dissection were performed at the Laboratory of Surgical NeuroAnatomy (LSNA) of the University of Barcelona (Fig.1) between 2007 and 2011 using operating microscopes (Zeiss OPMI 16 and Contraves; Carl Zeiss, Oberkochen, Germany) and a rigid endoscope (Karl Storz and Co., Tuttlingen, Germany) that was 4 mm in diameter, 30 cm in length and equipped with 0° and 45° lenses.

Figure 1

Laboratory of Surgical NeuroAnatomy (LSNA) of the University of Barcelona, Spain.

A real-time digital recording and editing system allowed creating high definition videos and photos of the entire dissection process. An integrated network connection provided for secure remote connectivity between the dissection Laboratory and other postproduction offices inside the Department (Fig.2).

Figure 2



Integrated network connection provided for connectivity between the Laboratory and the offices inside the Department

Skull base approaches dissection

Different (transcranial and endonasal) skull base approaches were performed:

Transcranial: Fronto-temporal, fronto-temporo-orbito-zygomatic, subtemporal trans-tentorial , retrosigmoid and transpetrosal approaches.

Endonasal: Extended endoscopic endonasal approach to the cribriform plate, spheno-ethmoidal planum, tuberculum sellae, sellar region, clival and craniovertebral junction.

In order to obtain the radiological images, a CT- scan was utilized; the cadaver’s heads were scanned using a section thickness of 0,6 mm and a gantry angle of zero, perpendicular to the palate, before and after the dissection. Therefore, four different steps were considered while developing the model protocol:

(a) A preliminary exploration of each specimen on a preoperative CT-scan in order to meaningfully analyze the individual variability of the anatomy using an open-source software for navigating in multidimensional DICOM images (Osirix®, Advanced open-Source PACS Workstation DICOM viewer).

(b) The creation of a computer-aided 3D model of the same specimen using specific imaging software for visualization and manipulation of biomedical data (Amira® Visage Imaging Inc., San Diego).

(c) The execution of the real approach in the dissection Laboratory on human cadaver heads.

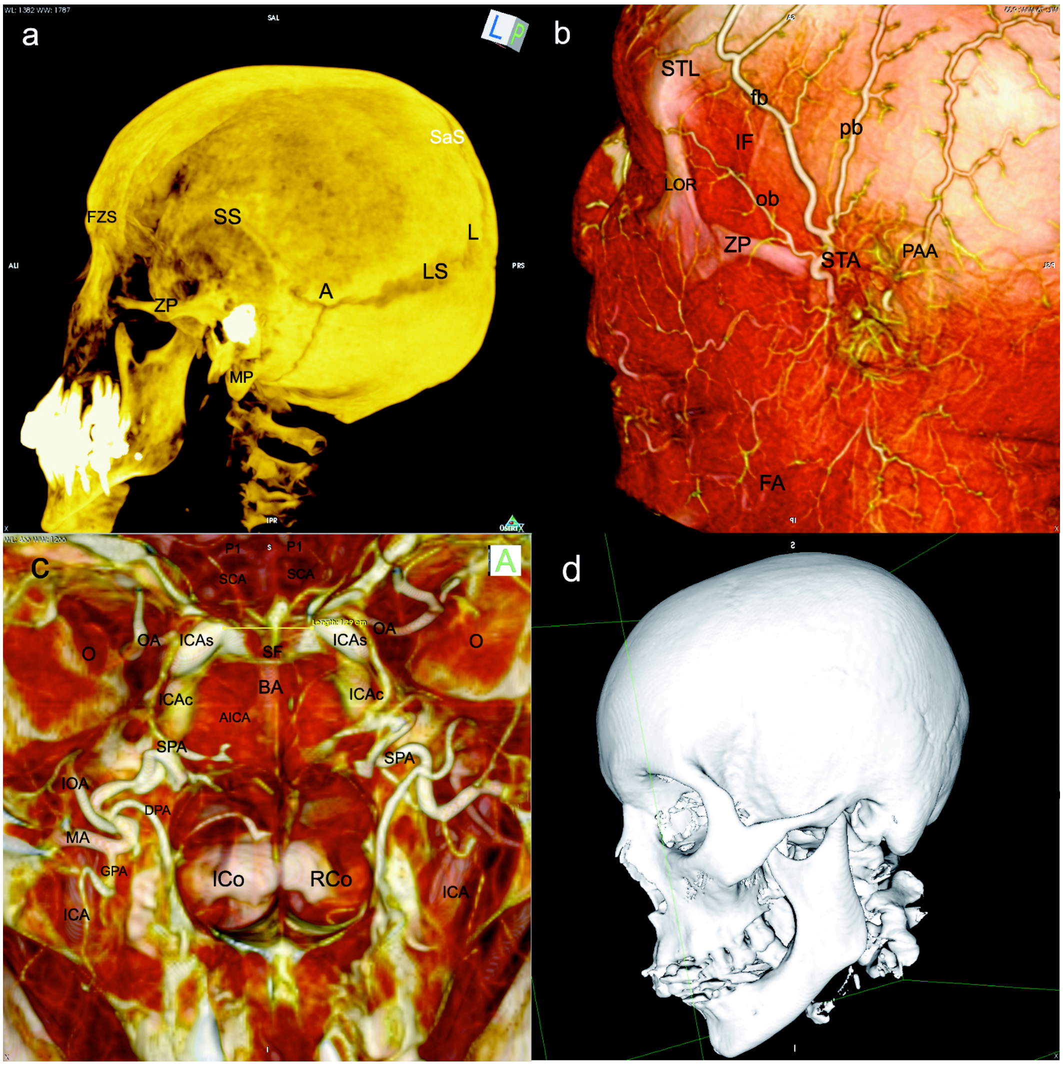
(d) The development of a 3D model from CT imaging of the specimen before and after dissection using the same imaging software as in point B. This reconstruction technique allowed to precisely re-design and reconstruct the approach realized in the dissection laboratory.

The total extracted bone volume of each procedure, as well as the surgical measurements, were quantified and compared to those obtained in the dissection lab. No significant measurement variation was encountered employing mechanical calipers and digital CT-based measurements.

The creation of three-dimensional model for skull base approaches. Preliminary steps

A virtual exploration of each specimen using the 3D reconstruction modules supported by the OsiriX software (Osirix®, Advanced open-Source PACS Workstation DICOM viewer) was performed in order to analyze the individual variability of the anatomy in each specimen. The *Maximum Intensity Projection,* the *Volume rendering* and the *Surface rendering* were the 3D reconstruction modules used to explore each specimen (Figure 3).

Figure 3



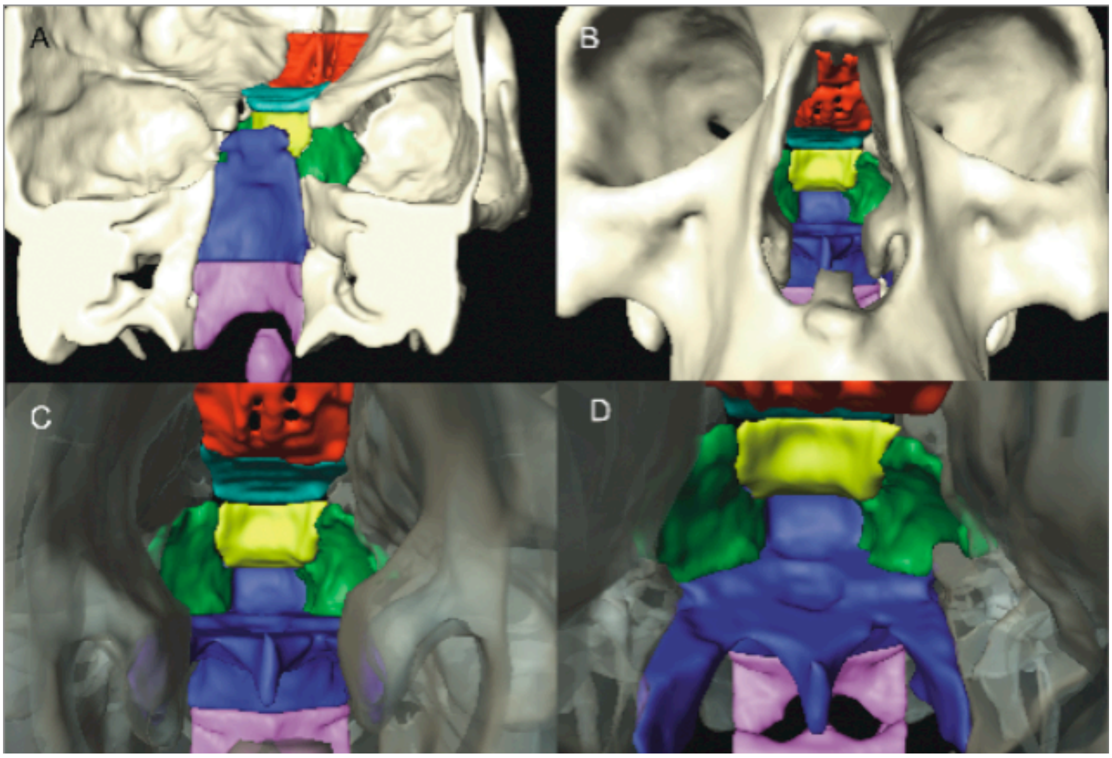
A virtual preliminary exploration of each specimen using the 3D reconstruction modules supported by the OsiriX software.

a) *Maximum Intensity Proyection*: A: asterion; SS: squamous suture; SaS: sagital suture; FZS: fronto-zygomatic suture; ZP: zygomatic process; MP: mastoid process; L: lambda; LS: lambdoid suture.
b) *Volume rendering:* STA: Superficial temporal artery; pb: parietal branch; fb: frontal branch; ob: orbital branch; PAA: posterior auricular artery; IF: infratemporal fossa; STL: superior temporal line; LOR: lateral orbital rim; ZP: zygomatic process.
c) *Volume rendering:* P1: precomunicant tract of the posterior cerebral artery; SCA: superior cerebellar artery; ICAs: parasellar tract of the internal carotid artery; ICAc: paraclival tract of the internal carotid artery; OA: ophtalmic artery; O: orbit; SF: sellar floor; BA: basilar artery; AICA: anterior inferior cerebellar artery; MA: maxillary artery; GPA: greater petrosal artery; DPA: descending palatine artery; IOA: infraorbital artery; SPA: sphenopalatine artery; lCo: left choana; rCo: right choana.
d) *Surface rendering:* external surface of the skull.

Thereafter, a computer generated 3D approach model of the specimen using specific imaging software for visualization and manipulation of biomedical data was created. In a first step, in order to construct the three-dimensional bone geometry of the skull, inner and outer bone surfaces of preoperative tomograms were segmented slice per slice with the help of a semi-automatic procedure based on threshold. Some specific small and thin anatomical regions such as *laminae*, vascular and nervous canals, nasal and paranasal sinuses as well as small orifices, were reconstructed manually. After every segmentation process, a smoothing function was also employed for a better display of the bone surfaces. In a second step, different volumes of interest (VOI) were labelled using the 3D editor to include the segmented bone representing a volume in order to create the computer surgical geometric triangular model. The creation of surface bone models with correct topology and optimized triangular shape from the segmented tomographic data was carried out automatically.

Once the VOIs have been defined and identified by labels using different colors, the virtual surgical approach can be designed. Each region gets a particular VOI type assigned which can be hidden sequentially in order to represent the different steps of the selected transcranial (Fig.4a and b) or endoscopic (Fig. 4c and d) approach.

Figure 4



Virtual computer-based 3D model of the different areas of the different endoscopic endonasal approaches to the midline skull base and cavernous sinus. RED Transcribiform approach; PALE BLUE Transplanum/Transtuberculum approach; YELLOW Sellar approach; DARK BLUE Transclival approach; PURPLE Craniovertebral junction approach; GREEN Cavernous sinus approach. (A) Posterolateral view ;(B) Anterior view; (C and D) Endonasal antero-inferior perspective.

After the preoperative model has been built and the surgical procedure has been simulated on the rehearsal system, the execution of the real approach in the dissection Laboratory was realized.

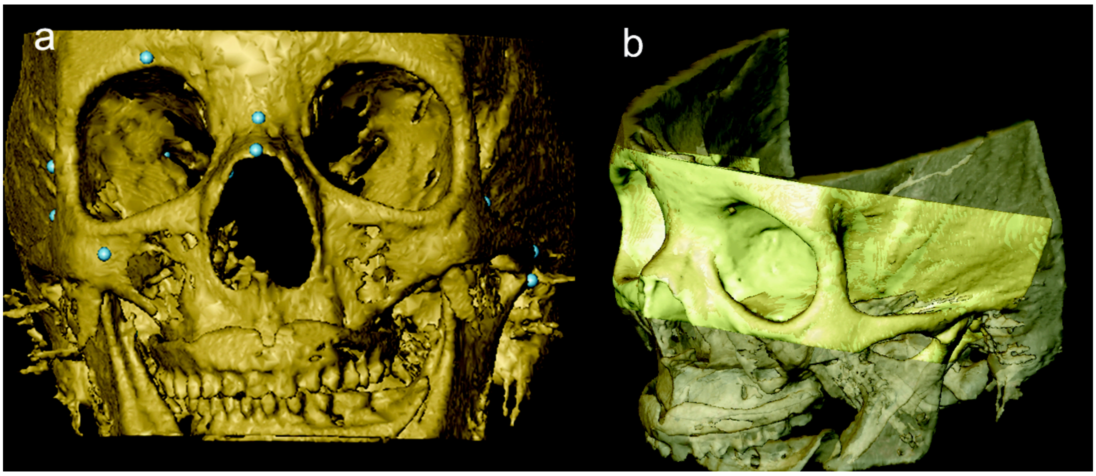
The creation of a 3D approach model obtained from CT imaging of the specimen before and after dissection.

The model was elaborated systematically by iterating the following steps.

Preoperative and postoperative indexed data collection in full DICOM format obtained from a computed tomographic scan of each specimen was used to generate the model. The bone structures form CT-scan were extracted and segmented with the help of a semi-automatic algorithm as previously described in the creation of the virtual model.

Thereafter, the pre- and post-operative CT scans were segmented independently and a rigid transformation including global translation, rotation and scaling was applied to align the data sets automatically. In selected cases a rigid registration using specific bone landmarks was computed (Fig.5a). This transformation process minimizes the squared distance between each pair of landmarks (Fig.5b). Corresponding landmarks can be defined in both data sets with Amira's *landmark editor*.

Figure 5

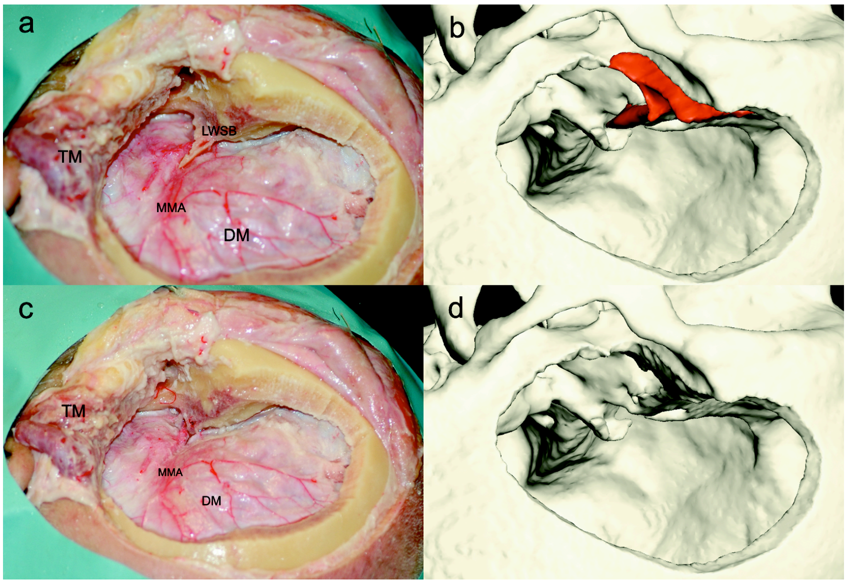


3D approach model obtained from CT imaging of the specimen before and after the dissection: Rigid transformation. Manual landmarks (a) and superposition of pre- and post-operative CT scan (B)

Once the rigid transformation was achieved, the final surgical model was obtained by re-segmentate the superposed postoperative bone surfaces and simulating the bone rearrangements.

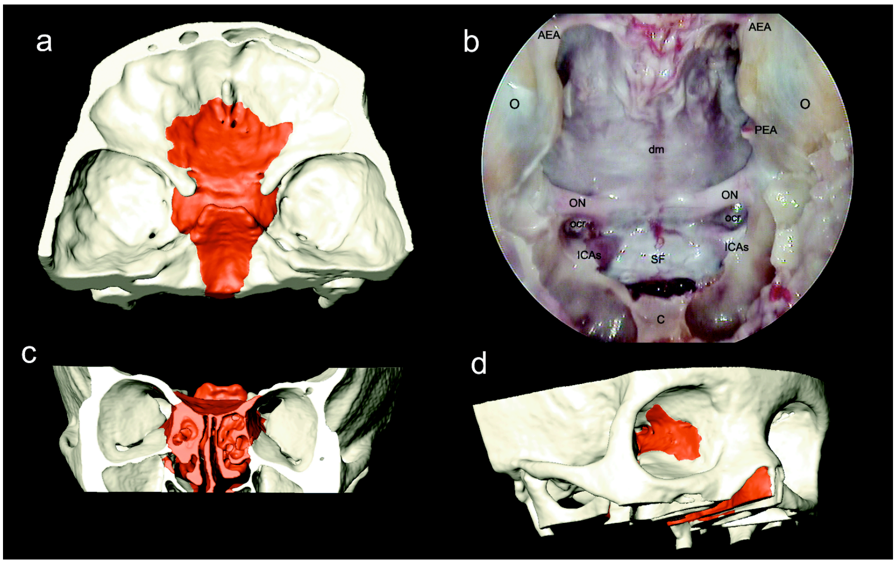
The total extracted bone volume of each transcranial (Fig. 6) or endonasal (Fig. 7) procedure, as well as surgical measurements, were analyzed and compared to those obtained in the dissection laboratory.

Figure 6



3D approach model obtained from CT imaging of the specimen before and after the dissection: The pterional approach. A: Comparison between laboratory dissection images and CT-based 3D reconstrucion of the pterional craniotomy before (A and B) and after (C and D) extradural drilling of the lesser wing of the sphenoid bone and of the anterior clinoid.

Figure 7



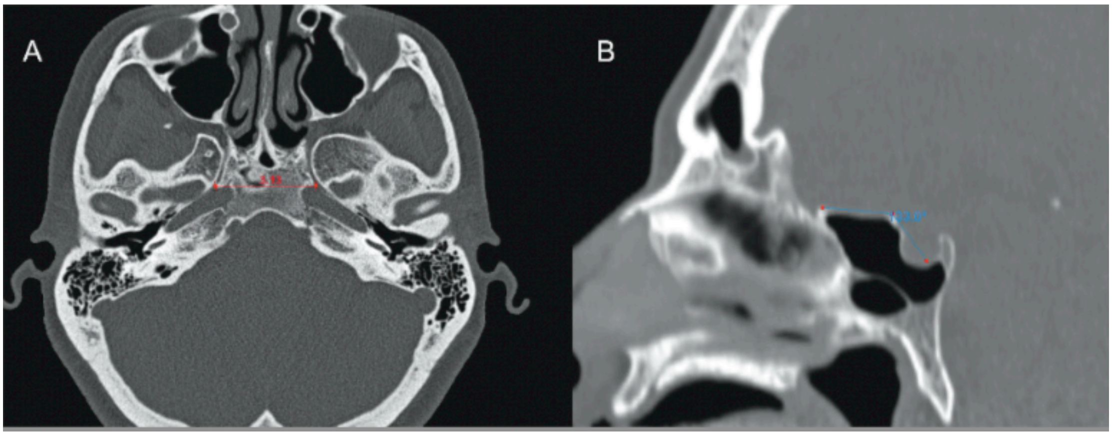
Real 3D approach model obtained from CT imaging of the specimen before and after the dissection: The endoscopic endonasal approach to the midline skull base. Comparison between the real approach (b) and the different perspectives of the CT-based reconstructed approach (a,c,d).

Linear and angular measurements were taken directly on the 3D-model (Fig.8a and b). Planar and spherical measurements, mainly utilized in the field of quantitative analysis, were employed to compare between different approaches [15-17]. The quantitative analysis of every approach was calculated employing our own developed 3D model based on two main parameters:

1. The area of exposure: considered as the maximal region defined on specific deep anatomic landmarks which can exposed using a definite surgical approach. (Fig.8a and b).

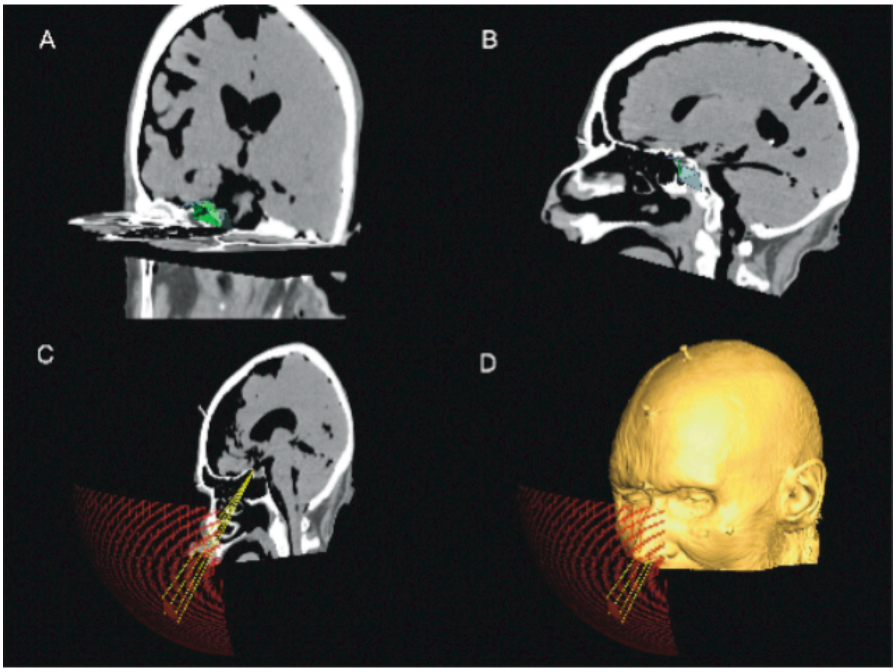
2. The surgical freedom: considered as an estimate of the movement available to the surgeon’s hands and instruments, represented by a partial spherical area through which surgical instruments can be inserted to manipulate a deep target (Fig.9c and d).

Figure 8



CT-scan showing the calculation of linear and angular measurements. (A) Distance between the pterygoid canals at level of the intrapetrous carotid canal. (B) The angle between the anterior skull base and the limbus sphenoidale.

Figure 9



Planar and spherical measurements obtained using the 3D reconstruction modules supported by the Amira software. (A) Virtual computer-based multiplanar reconstruction with measurement of area of exposure for the endoscopic endonasal to the sellar region. (B) Virtual computer-based sagittal reconstruction disclosing the representation of the area of exposure for the an endoscopic endonasal to the sellar region (C) Virtual computer-based reconstruction of the surgical freedom obtained for a point at level of the tuberculum sellae during an endoscopic endonasal approach. (D) Volume rendering of the same specimen as in figure C to demostrate the surgical route through right nostril.

White matter brain dissection

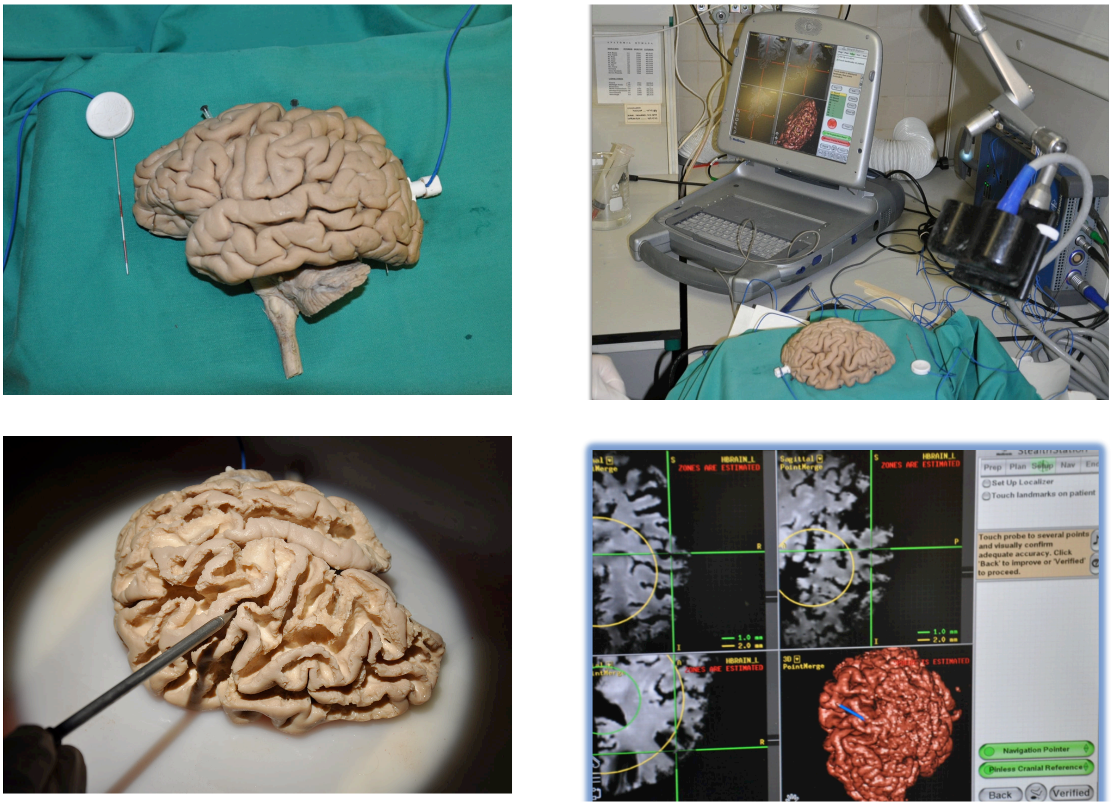
The formalin fixed brain hemispheres were dissected according to the Klingker method[18]. Before each dissection, a structural ultra-high magnetic field 7 and 1,5 Tesla Magnetic Resonance Imaging (MRI) and a tractographic reconstruction was performed in each hemisphere in order to create a three-dimensional geometrical model of the main white matter connections and to perform specific measurements between the main white matter landmarks [24,25].

Afterwards, a preliminary, carefully analysis of the pre-dissection MRI, using the Dextroscope® virtual reality system for neurosurgical planning was realized to meaningfully evaluate the anatomical individual variability of each brain structure (external configuration as well as white matter fibers).

The next step was the microanatomical dissection of each brain with the assistance of a Neuronavigation System [21], using Klingler's traditional technique. We apply a specific protocol of dissection including the main target structures for the white matter according to different surgical approaches. All steps of dissection were documented with a digital camera and the accuracy of MRI findings was measured with the neuronavigation system. A morphologic analytic study, as well as a set of surgical measurements was collected per each specimen.

In the last step we have compared the results from the dissection lab with those obtained from the structural ultra-high magnetic field 7 and 1,5 Tesla MRI (Fig.10).

Figure 10



Touch probe to several points and visually confirm adequate accuracy. Click 'Back' to improve or 'Verified' to proceed.

Microanatomical dissection of each hemisphere with the assistance of an Image Guidance Neuronavigation System, using Klingler's traditional technique.

Results

In the present study we have developed a model for the surgical training in the anatomical laboratory based in three main principles. *Cadaver dissection*: the skull base surgeon requires specific training to achieve competency in neurosurgery. Basic skills such as craniotomies, craniectomies and advanced drill techniques should be acquired during an irreplaceable cadaver dissection experience. Once acquired these fundamentals skills they can be also learned on 3D advanced simulations but dissection on cadavers still remains a precious experience which cannot afford to be missed even in this era of the great medical advances. *Virtual surgery simulation system*: During neurosurgical approaches, the operative field is mostly viewed by means of a microscope or an endoscope in which a small camera relays a video signal to a 2D monitor. During endoscopic surgery, however, the surgeon's direct view is often restricted, thus requiring a higher degree of manual dexterity. The complexity of the instrument controls, restricted vision and mobility, difficult hand-eye coordination, are major obstacles in performing such procedures. To date, a number of techniques have been developed for the assessment of manual dexterity and hand-eye coordination with the combined use of virtual and mixed reality simulators. These environments offer the opportunity for safe, repeated practice and for objective measurement of performance. Intermediate and advanced skills require simulations using more sophisticated models such as 3D advanced neuroimaging techniques and virtual reality computer systems. *Postdissection analysis and quantification of data*: this step provides the actual quantification of the approach realized in the dissection laboratory. Data analysis is a fundamental step toward interpreting and critiquing results. In our experience the data analysis improve the general knowledge and gives us the opportunity to compare different neurosurgical approaches in terms of effectiveness to reach the surgical target.

The present model results very effective, providing a depiction of anatomical landmarks as well as a 3D visual feedback, thus improving the study, design and the execution in a variety neurosurgical approaches.

Discussion

Skull base approaches

Development of the three-dimensional imaging method in the study of surgical anatomy has become a crucial tool particularly for visualizing the morphological data of medical images.

We have created a virtual surgery environment for neurosurgical approaches to augment surgical education and provide for preoperative rehearsal of procedures. In order to be safe and effective, the surgeon must have a complete understanding of the complex anatomy involved in each approach. However, limitations in acquiring and storing cadaveric material, recent pressures in training opportunities, and progress in digital image technology have led to advances in virtual or artificial visual means to augment surgical training [7-13]. Indeed, for training neurosurgeons, the appearance of reality is still crucial for learning anatomic structures and procedures. Such an understanding is difficult to acquire only with traditional one or two-dimensional images. Concerning this aspect, the efforts in capturing human body knowledge and constructing body models can be categorized in three main generations. The first generation includes print text materials. The second generation covers early multi-media formats, typically 2D images. The third generation refers to computer applications with 3D views and user-generated models. These applications can generate and export images to the first and second generations. The print presentation is static, non expandable, and non transferable. Structures are not segmented and typically a few locations only are marked with the labels. The number of views is limited. The spatial relationships are hard to grasp. Mapping of the print content onto the patient (or specimen)-specific data is not feasible. The second generation partially overcomes these limitations but works only with two-dimensional images. A third generation application allows the investigator to generate views by manipulating the model and applying cropping planes and/or voxel editing onto the patient (or specimen)-specific data.

For these reasons, the application of an immersive third generation computer simulation environment is becoming a natural fit for providing education in every surgical specialty [13,26]. In the present study, a highly interactive software system for 3D data analysis, visualization and geometry reconstruction has been identified to perform 3D reconstruction from medical imaging data. It enables development of new generation systems for rapid and intelligent exploration of complex skull base approaches models in real time with dynamic scene compositing from highly parcellated 3D models, continuous navigation and manipulation-independent labeling with multiple features. Measurements obtained from CT images can be used preoperatively to help analyze the extent of bone removal in order to develop surgical practice guidelines as an approach to evidence-based surgery.

White matter approaches

The implementation of Image Guidance Systems significantly improve our dissections and gave a required insight into the spatial 3D arrangement of white matter tracts. The accuracy of dissection and the possibility to compare information and measurements from the ultra-high magnetic field 7 Tesla MRI with the same dissected specimen has provided a valuable knowledge than the classical methods. Above all, we believe that the “Ex-Vivo Interactive Image Guided Dissection” (EVIGD) can add a new dimension to anatomical descriptions of the human brain. Further studies will be needed to demonstrate conclusively the relationships between white matter fibers in cadavers and tractographic studies obtained from 7 Tesla MRI of the same specimen.

Conclusions

The present model results very effective, providing a depiction of anatomical landmarks as well as a 3D visual feedback, thus improving the study, design and the execution in a variety of neurosurgical approaches. Such system can also be utilized as:

1) A pre-operative planning tool that can allow the neurosurgeon to perceive, practice reasoning and manipulate 3D representations of the skull base and white matter anatomy.
2) An advanced tool for analytical purposes: the model allow to perform different types of pre- intra- and postoperative measurements between surgical landmarks, mainly utilized in the field of quantitative analysis: linear, angular, planar and spherical measurements.
3) A post-operative tool for training purposes, indeed the visual feedback retrieved from the overlapping of pre- and post-dissection images can be extremely helpful in defining the boundaries of the main neurosurgical approaches, disclosing a detailed view of the structures that determine them.

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