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EDUCATION & TRAINING

Interactive 3D-PDF Presentations for the Simulation and Quantification of Extended Endoscopic Endonasal Surgical Approaches

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Abstract A three-dimensional (3D) model of the skull base was reconstructed from the pre- and post-dissection head CT images and embedded in a Portable Document Format (PDF) file, which can be opened by freely available software and used offline. The CT images were segmented using a specific 3D software platform for biomedical data, and the resulting 3D geometrical models of anatomical structures were used for dual purpose: to simulate the extended endoscopic endonasal transsphenoidal approaches and to perform the quantitative analysis of the procedures. The analysis consisted of bone removal quantification and the calculation of quantitative parameters (surgical freedom and exposure area) of each procedure. The results are presented in three PDF documents containing JavaScript-based functions. The 3D-PDF files include reconstructions of the nasal structures (nasal septum, vomer, middle turbinates), the bony structures of the anterior skull base and maxillofacial region and partial reconstructions of the optic nerve, the hypoglossal and vidian canals and the internal carotid arteries. Alongside the anatomical model, axial, sagittal and coronal CT images are shown. Interactive 3D presentations were created to explain the surgery and the associated quantification methods step-by-step. The resulting 3D-PDF files allow the user to interact with the model through easily available software, free of charge and in an intuitive manner. The files are available for offline use on a personal computer and no previous specialized knowledge in informatics is required. The documents can be downloaded at http://hdl.handle.net/2445/55224.

Keywords Endoscopic endonasal transsphenoidal surgery · Anatomical reconstruction · 3D-PDF · Skull base · Quantitative analysis · Surgical freedom · Exposure area · Surgery simulation · Neurosurgery · 3D reconstruction

This article is part of the Topical Collection on *Education & Training*

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Introduction

Significant technological advances have been made in recent years, introducing innovative teaching and learning techniques into health sciences, in particular to medicine. Image processing techniques allow the reconstruction of three dimensional (3D) anatomical models from conventional two dimensional (2D) images, thereby optimizing spatial perception of the underlying anatomy. Studies have shown that 3D model reconstructions offer better visualization quality, and improve anatomy understanding [1, 2] and have become an indispensable tool in medicine, particularly in neurosurgical training [3, 4].

At present, 3D models obtained from cross-sectional images can be embedded in Portable Document Format (PDF) files, becoming a powerful tool for clinical, educational and

research purposes [5]. Some 3D models based on experimental animals have been developed and presented in PDF format [6, 7]; such technology has been also implemented to study the embryonic development of a human heart [8–10] and anatomy of a whole human embryo [11]. Human 3D resources based on images from dissections of the Visible Human Project [12] are available [13]. Furthermore, 3D-PDF resources from the Korean Visible Body, based on higher resolution images of sections of a whole male cadaver, are now also freely available [14]. 3D-PDF technology was also recently used in neurology (brain and face PDFs [15]), orthodontics [16] and radiology [5].

We have previously created a virtual 3D model of lumbar spine of anesthetic interest and reported the advantages of using PDF format for its presentation [17, 18].

Here, we present the first 3D-PDF model that simulates a surgical procedure. For the simulation we use the 3D skull base model previously reported by our group [19, 20] that has been applied to the extended endoscopic endonasal approaches to the midline skull base and cavernous sinus [21]. The quantitative analysis of different approaches has been performed [22, 23] and the resulting models have been embedded into three 3D-PDF documents to visualize and simulate the surgical steps and quantification methods.

Methods

This work was based on data obtained in previous studies from DICOM files, whose CT setting details, basic 3D reconstruction and quantitative analysis have been previously published [21, 22].

Methodology of this study can be divided into 3 main steps (Fig. 1): data acquisition (a), image processing (segmentation and surface reconstruction) and quantitative analysis (b) and 3D-PDF document creation (c).

Data acquisition

The data was acquired during 18 dissections of formalin-fixed cadaveric heads. Dissections were performed at the Laboratory of Surgical NeuroAnatomy (LSNA) of the University of Barcelona, Spain. The procedure consisted of classical endoscopic endonasal transsphenoidal approach to the midline skull base combined with the extended approaches targeting the entire skull base from the most anterior areas to the craniovertebral junction. The surgery was performed using a rigid endoscope 4 mm in diameter, 18 cm in length, with 0-degree optics (Karl Storz, Tuttlingen, Germany).

Pre- and post-dissection CT scans were acquired on a SOMATOM Sensation 64 Scanner (Siemens, Forchheim, Germany), using the multislice helical acquisition protocol (64 slices, slice thickness 0.6 mm, gantry angle 0 degrees).
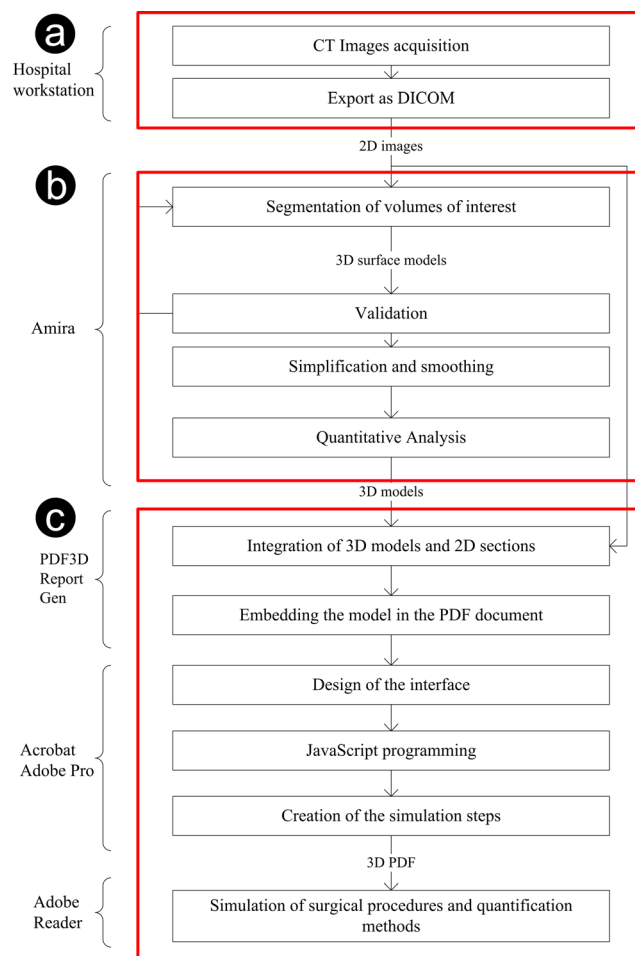

Fig. 1 Process flow diagram: data acquisition (**a**), image processing (**b**), 3D-PDF technology (**d**)

A neuronavigation system (Stealth Station; Medtronic Sofamor Danek, Memphis, TN) was used in order to obtain exact coordinates of particular anatomical landmarks which were later used for quantitative analysis. Five screws were implanted in the skull as permanent bone reference markers to allow the co-registration with the neuronavigation system.

3D model reconstruction

CT images were exported from the hospital equipment to the neuroanatomic laboratory in DICOM format, which preserves spatial coordinates. Data processing was performed by the software AMIRA® v5.2 (Mercury Co, Boston, USA), installed on a graphic station (Dell Precision 690). This software is designed for visualization and analysis of biomedical images, allowing volumetric reconstruction.

The image processing steps are the summarized in Fig. 2:

1.) CT images in different planes, saved in DICOM format on the CT equipment are imported to AMIRA software (Fig. 2.1)

Fig. 2 Image processing steps (2.1–2.4) and the initial 3D-PDF view of the model (2.5)
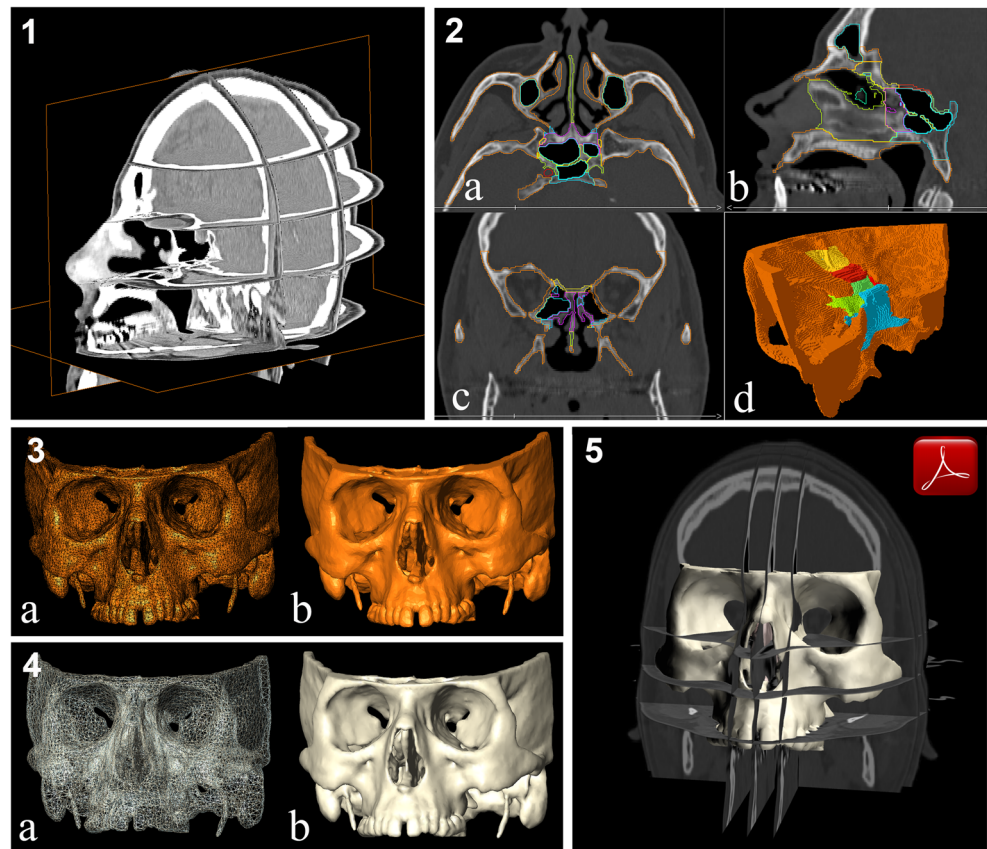
2.) The images in the three orthogonal planes - axial (Fig. 2.2a), sagittal (Fig. 2.2b) or coronal (Fig. 2.2c) - are segmented by automatic and manual delimitation of volumes of interest (VOI) of skull base and nasal structures. A preliminary 3D visualization (Fig. 2.2d) is prepared for revision of the correspondence between each model contours and its corresponding structure in the CT images. Steps can be repeated until accurate adjustment is reached.

3.) 3D appearance results from triangulation by marching cubes algorithm (Fig. 2.3a), that leads to the corresponding shaded 3D surface model (Fig. 2.3b).

4.) In order to allow a quick interactive movement of the model, the number of triangles is reduced (final resolution about 1 mm^2 per triangle) and a whole structure smoothing is applied (Fig. 2.4a), resulting in a simplified 3D surface (Fig. 2.4b).

5.) Once the 3D reconstruction has been finished, the triangular models are exported to the Virtual Reality Modeling Language (VRML) file format. In addition to the reconstructed anatomical structures various axial, coronal and sagittal CT slices were included in the final model to serve as anatomical references (Fig. 2.5). VRML files are converted to Universal 3D (U3D) format by a generator of 3D-PDF files called PDF3DReportGen (Visual Technology Services Ltd, Berkshire, United Kingdom),

and embedded in a 3D area of a PDF file by Acrobat XI Pro.

Quantitative analysis

Quantitative analysis was performed using the same software (Amira® v5.2). Firstly, bone removal was measured by overlapping the 3D models reconstructed from the pre-dissection and post-dissection CT data. Secondly, the x, y and z (Cartesian) coordinates of the specific anatomical structures recorded during the surgery exported from the neuronavigation computerized tracking system were used to calculate the quantification parameters.

Two parameters were defined:

– Area of exposure: defined as the maximal region defined on specific deep anatomic landmarks that can be exposed using a particular surgical approach, and
– Surgical freedom: 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 specific deep target

These parameters were calculated for three different variations of the approach to the sellar region of the skull base: in

each variation an additional nasal structure was removed (from no removal of nasal structures to adding bilateral middle turbinectomy and finally adding bilateral ethmoidectomy).

The exposure area is calculated by performing the following steps:

1. Four fixed and six variable point coordinates of anatomical landmarks are collected using the neuronavigation system during an endoscopic endonasal approach without removal of any nasal structure;
2. A total of ten triangles were constructed by connecting the fixed and variable points;
3. An irregular polygonal surface representing the working area of the endoscopic endonasal approach, without removal of any nasal structure, was then created;
4. Changing only the variable coordinates, the polygon surface representing the working area after a middle turbinectomy was obtained;
5. After changing again only the variable coordinates, the polygon surface representing the working area after an ethmoidectomy was obtained

The protocol for surgical freedom quantification was the following:

1. A microdissector (15 mm in length) with its tip placed on a defined deep target landmark—the T point— was rotated circumferentially and four coordinates were recorded on its free end at the moment of maximal displacement;
2. The rendered surface area (rhomboid) connecting the four points was created and divided into a triangular mesh;
3. A spherical segment was created starting from the deep T target point;
4. The triangular mesh was projected over the spherical segment;
5. The resulting spherical segment area represents the surgical freedom of each specific T point coordinate

All data obtained by quantitative analysis was then exported to VRML format to be included in PDF-3D files.

3D-PDF documents creation

The 3D geometrical models and CT images were converted to the PDF documents by the PDF3D Report Generator (Visual Technology Services Ltd., Ascot, Berkshire, UK). Adobe Acrobat XI Pro was used to define the interface of the custom made template containing interactive fields. JavaScript programming was used to customize interactive buttons and to create tools for surgery simulation. For this purpose around 60 JavaScript functions were developed. The JavaScript 3D engine uses different objects, properties and methods of the

JavaScript™ extensions for Adobe® Acrobat® Professional, Acrobat Standard and Adobe Reader®, documented in Adobe API References [24, 25].

Results

Three PDF-3D documents were created: one for the surgery simulation and one for each quantification parameter.

The PDF documents with the 3D models can be accessed from the University of Barcelona public repository (http://hdl.handle.net/2445/55224). These files are distributed under an international Creative Commons Attribution-Share Alike (CC BY-NC-SA 2.0) license, which requires attribution to the authors, but allows derivate works without commercial use, provided that it is shared like the present document. JavaScript source code and original surface models are not public and cannot be accessed or modified.

The resulting PDF-3D files must be downloaded and saved in the same folder on a computer. The files should be opened by Adobe Reader XI or superior to achieve the optimal functionality.

The complete model includes the reconstructions of nasal structures (nasal septum, vomer, middle turbinates), bony structures of the anterior skull base and maxillofacial region, including the main paranasal sinuses (ethmoid cells, sphenoid sinus) as well as the partial reconstructions of the optic nerve, the hypoglossal and vidian canals and the internal carotid arteries. Furthermore, it includes axial, sagittal and coronal CT images.

The interface of the PDF document is divided into three main functional areas (Fig. 3): central screen 3D working area (a), control area for the interaction with the model (b) and presentation area (c).

Central screen 3D working area is where the skull base model is visualized and can be rotated in 360°, zoomed in and out or translated. Pre-defined axial, sagittal and coronal views are offered as reference.

Control area, at the left, offers the possibility to position the model in one of default views (anterior, lateral, superior, posterior) and to change the properties of the anatomical structures by partial transparency effects and selective visualization. Different axial, sagittal, and coronal CT slices can be visualized either independently or in combination.

Presentation area contains controls that reproduce a presentation with predetermined custom views. When the presentation is active a textual description of the current view appears below the arrows. Tools for making modifications to the existing presentation are also located here. This section is crucial for simulation of the surgery, as it contains the explanation of each step performed.

Simulation of the surgery is achieved by showing the relevant anatomical structures in a predetermined position at each

Fig. 3 The PDF file interface is organized in 3 functional areas: screen working area (**a**), control area (**b**) and presentation area (**c**)
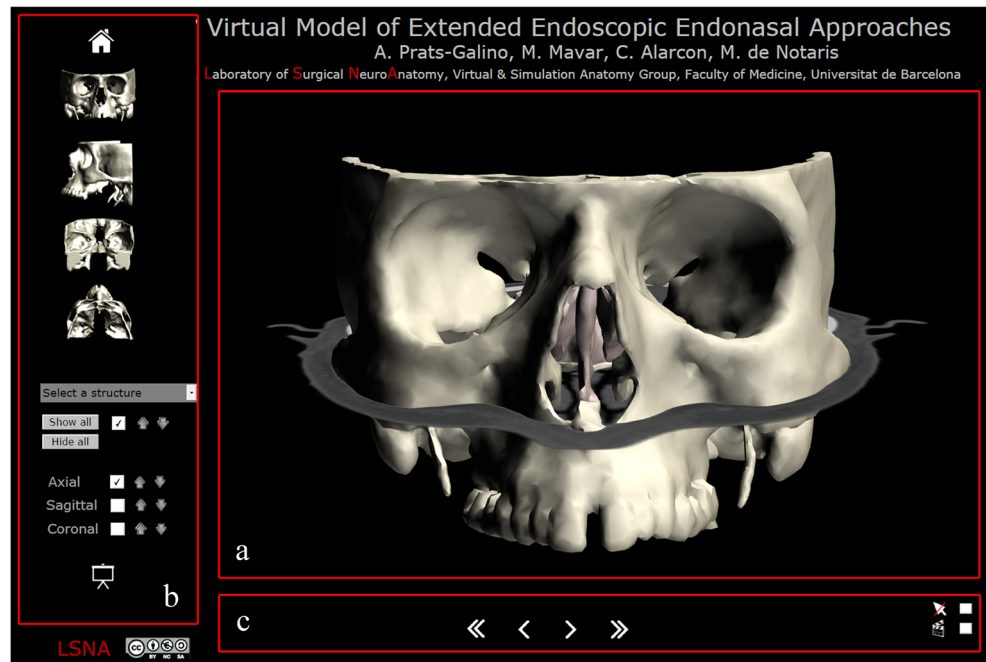
step during the surgery. The structures are accompanied by a CT image when it is useful to observe their correspondence. During an endoscopic endonasal transsphenoidal surgery various nasal structures are being removed and the surgeon has to be careful not to touch any of the important structures (nerves, arteries etc.) nearby. In our presentation we show which structure is removed at which step and what the main anatomical relations between adjacent structures are (Fig. 4): an adequate surgical corridor is obtained by performing removal of posterior nasal septum (Fig. 4a), bilateral ethmoidectomy (Fig. 4b), anterior sphenoidotomy (Fig. 4c) and drilling of sphenoid sinus septa (Fig. 4d), where the structure removed (sinus septa) is located in close proximity with internal carotid arteries, within the sphenoidal sinus.

After the surgical corridor has been opened, different extended endoscopic endonasal approaches to the midline skull base and the cavernous sinus are possible: endonasal view (Fig. 5a) and transcranial view (Fig. 5b).

For each extended endoscopic endonasal approach the bone removal was calculated by superimposing the surface reconstructed from the pre- and post-dissection CT data. The volume of the removed bone is depicted in color (Fig. 5a and b) for each approach.

Quantification analysis methodology is represented in two separate 3D-PDFs. They both contain the 3D reconstruction of the central part of the skull base, the main focus being sella turcica, a target point of the surgical approaches performed.

The steps for quantification parameters calculation explained in the Methodology section were simulated by interactive 3D-PDF presentations (Figs. 6 and 7).

The fixed and variable coordinates of the anatomical landmarks collected by the neuronavigation system for calculation of the exposure area can be observed in Fig. 6b. By connecting them into triangles an irregular polygonal surface is created, representing the exposure area without removal of any nasal structure (Fig. 6c) and the exposure area after performing bilateral turbinectomy and bilateral ethmoidectomy (Fig. 6d).

To calculate the surgical freedom, the model of the probe (microdissector) has been reconstructed and is shown alongside skull base surface and a sagittal CT image (Fig. 7). The point coordinates on the free end of the probe are connected into a triangular mesh (Fig. 7a), after which a sphere with center in the deep target point (sellar floor) is created (Fig. 7b). The triangular mesh is projected to the sphere (Fig. 7c), and the resulting partial sphere represents the surgical freedom for a particular approach.

During all presentations it is possible to interact with the model, zoom in on the structures of interest and move along successive CT planes.

Discussion

Although anatomic laboratory dissection remains the gold standard in surgical training, it has lately been extensively upgraded by modern imaging systems. These systems enable computerized reconstructions and provide the surgeons with the ability to analyze all the anatomic data in a safe, virtual, 3D dynamic system [26–29].

Fig. 4 Simulation of endoscopic endonasal surgery, removing nasal structures in order to open a surgical corridor: posterior nasal septum (**a**), ethmoid cells (**b**), anterior sphenoid sinus wall (**c**) and sphenoid sinus septa (**d**)
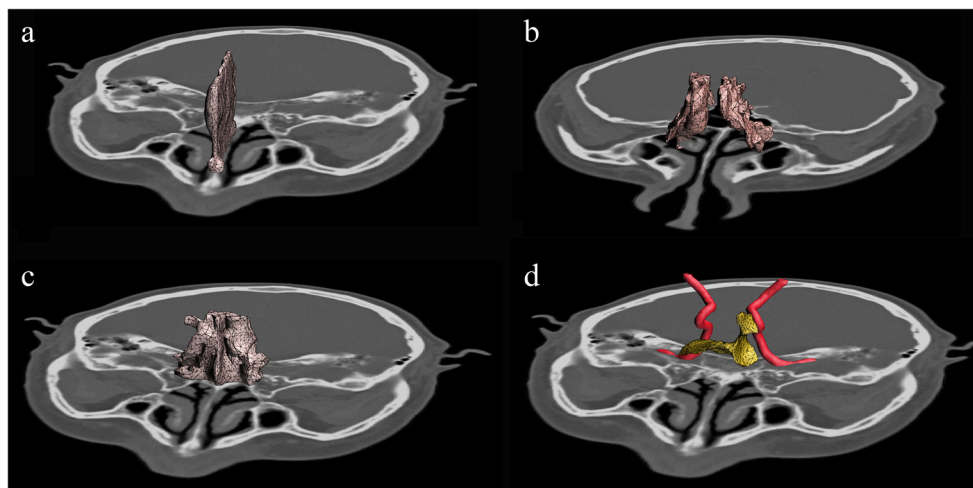
We have developed a computer-based 3D anatomic model to study its effect on enhancing surgical approaches [20, 21] and surgical training [29]. This model has been employed during various dissection studies of our group [19, 30, 31]. It was shown that the application of the 3D computer-based model to the endoscopic endonasal transsphenoidal approach allowed us to analyze, in an objective way, the main features of the surgical technique in relation to the pertinent anatomy. The 3D model offered the possibility to study in detail the surgical anatomy in a realistic surgical training rehearsal with an excellent spatial perception.

Furthermore, this model allowed the post-dissection analysis and quantification of data [22, 23], which improves the general knowledge about the procedure and give us the opportunity to compare the skull base surgical approaches.

In the present study the previously described 3D model was embedded into highly compatible PDF files. Moreover, the authors have created tools that guide us through the steps of the surgery and increase the understanding of the endoscopic endonasal approach to the skull base. Additionally, the 3D-PDF files were created to explain the methodology of the quantification analysis in a highly understandable way. The relatively complex process of obtaining quantification parameters was divided into simple steps simulated by illustrative and clear 3D model views.

The advantages of the presented method are the free availability and the anatomical detail based on human CT images, focused to endoscopic endonasal surgical approaches. The resulting files are standard PDF files that can be opened by freely available programs (Acrobat Reader XI or posterior). The format of the documents simplifies their use, portability and storage as the file size can be compressed, but for the moment, 3D-PDF documents are not supported in mobile devices (tablets and smartphones).

In comparison to the similar 3D-PDF resources in medicine [5, 9–11, 14, 15] the presented files have an advanced interface that optimizes the interaction with the 3D model and provide additional information in form of the 3D presentation. They are intuitive and don't require any special informatics knowledge of the user who can be familiarized with the interface in a few minutes.

Altogether, these documents may be of special interest for neurosurgeons and neurosurgery teaching. They can be used for preoperative planning that would allow the neurosurgeon

Fig. 5 Extended endoscopic endonasal approaches to the midline skull base and the cavernous sinus: endonasal view (**a**) and transcranial view (**b**). Standard sellar approach (*yellow*), transcribriform (*red*) and transplanum/transtuberculum approach (*blue*), cavernous sinus approach (*green*), transclival approach (*purple*), upper and lower craniocervical junction approach (*light purple*)
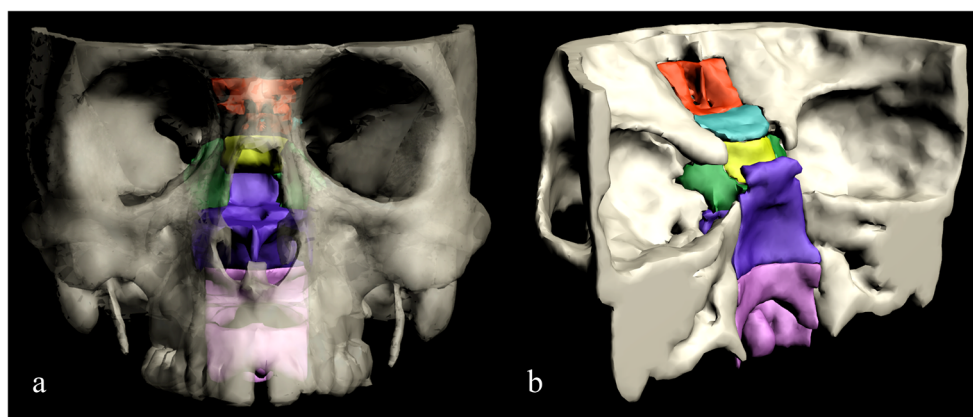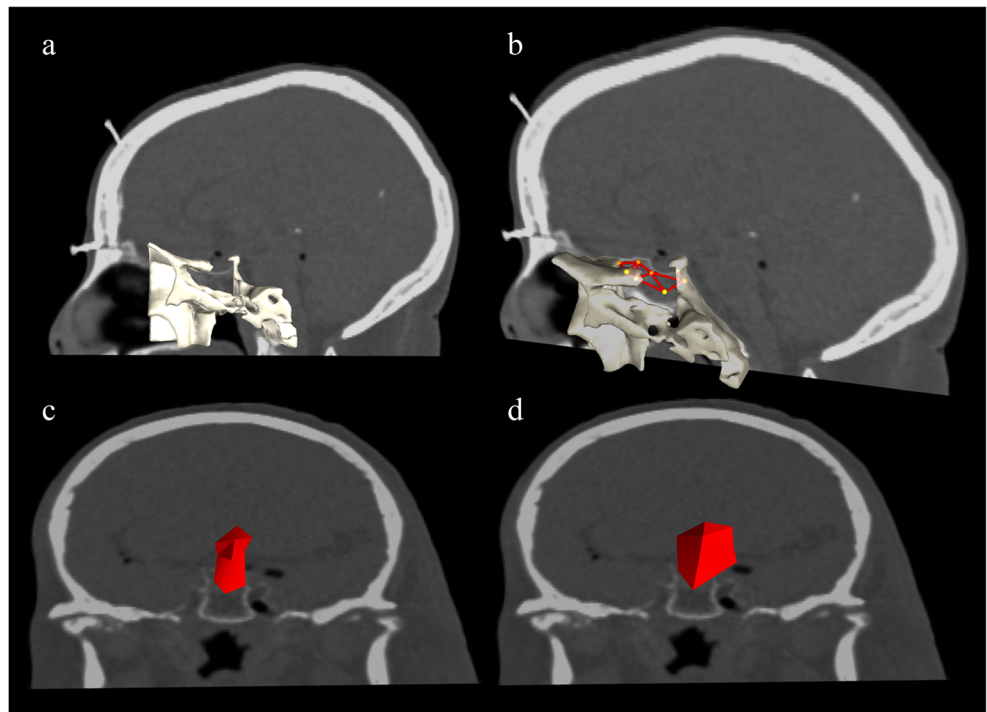
Fig 6 Exposure area quantification steps

to perceive, practice reasoning, and manipulate 3D representations of the anatomy. They could also be used in teaching as a convenient education material, or as a visual support in research programs.

Conclusions

The intuitive 3D-PDF interactive anatomical models allow the visualization of skull base structures from any perspective,

Fig. 7 Surgical freedom quantification steps
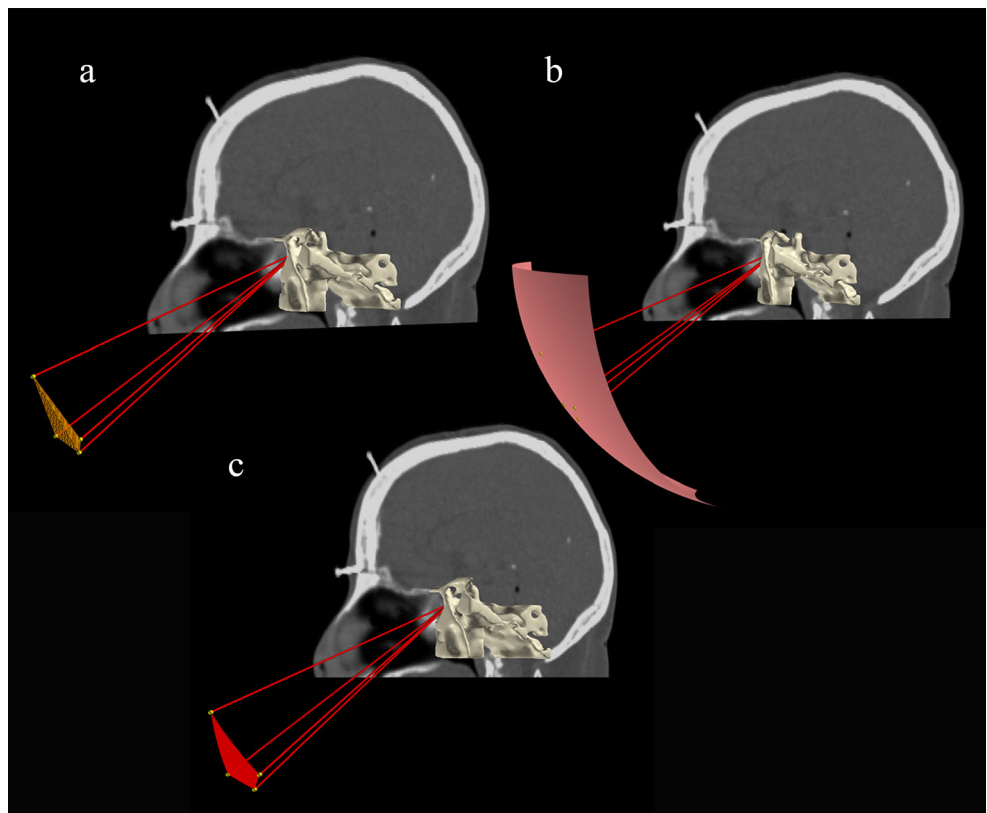
alongside CT images. They contain interactive presentations explaining the steps of the endoscopic endonasal surgery and the associated quantification methods. The models can be examined through easily available software, free of charge, don't require previous informatics knowledge and are available for offline use. They are of special interest in neurosurgical planning and teaching.

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