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Three-dimensional stereotactic atlas of the adult human skull correlated with the brain, cranial nerves, and intracranial vasculature

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HIGHLIGHTS

- A new, interactive and stereotactic 3D atlas of adult human skull is constructed.
- Skull is spatially correlated with brain, cranial nerves, and intracranial vessels.
- The skull model is complete with all 29 bones, including the auditory ossicles.
- The skull contains all typical bony features and landmarks.
- Superior to existing skull models in completeness, realism, and brain integration.
- Valuable for medical students and residents to easily get familiarized with skull.
- Surrounding anatomy can be explored with a few clicks.
- It may potentially serve as a reference aid in the reading and operating rooms.

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ABSTRACT

Background: Although the adult human skull is a complex and multifunctional structure, its 3D, complete, realistic, and stereotactic atlas has not yet been created. This work addresses the construction of a 3D interactive atlas of the adult human skull spatially correlated with the brain, cranial nerves, and intracranial vasculature.

New method: The process of atlas construction included computed tomography (CT) high-resolution scan acquisition, skull extraction, skull parcellation, 3D disarticulated bone surface modeling, 3D model simplification, brain–skull registration, 3D surface editing, 3D surface naming and color-coding, integration of the CT-derived 3D bony models with the existing brain atlas, and validation.

Results: The virtual skull model created is complete with all 29 bones, including the auditory ossicles (being among the smallest bones). It contains all typical bony features and landmarks.

Comparison with existing method(s): The created skull model is superior to the existing skull models in terms of completeness, realism, and integration with the brain along with blood vessels and cranial nerves.

Conclusions: This skull atlas is valuable for medical students and residents to easily get familiarized with the skull and surrounding anatomy with a few clicks. The atlas is also useful for educators to prepare teaching materials. It may potentially serve as a reference aid in the reading and operating rooms.

1. Introduction

The adult human skull is a complex and multifunctional structure. Depending on source, the skull is formed by 28 (Standring, 2008) or 29 bones (Steele and Bramblett, 2007) that are divided into the bones holding and protecting the brain (cranial bones, neurocranium) and the bones of the face (facial bones, viscerocranium). The majority of the bones in the skull are immovably joined and

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they are separated from each other by sutures. The complexity of these serrated sutures increases from the inner to outer surface (Standring, 2008). The skull contains numerous foramina and canals—openings through which blood vessels, cranial nerves, and other structures pass in and out of it. Each disarticulated bone has its respective features and landmarks (Steele and Bramblett, 2007), including (besides abovementioned foramina and canals) notches, fissures, ducts, processes, eminences, crests, wings, grooves for blood vessels and dural sinuses, impressions of cerebral gyri, and depressions for arachnoid granulations. The complexity of the skull base, in particular, presents surgical challenges for neurosurgeons and otolaryngologists. To our best knowledge, a 3D, complete, realistic, and stereotactic atlas of the adult human skull has not yet been created.

Our overall objective is to construct an advanced, 3D, reference, holistic, detailed, accurate, realistic, high resolution, fully parcellated, completely labeled, spatially consistent, stereotactic, interactive, user friendly, extendable, composable, dissectible, explorable, and scalable atlas of the whole adult human brain along with the head and neck.

We had earlier developed a 3D brain atlas from multiple magnetic resonance (MR) 3 and 7 Tesla *in vivo* scans of a single brain specimen. The atlas allows the user to explore any region of interest along with its surroundings just with a few clicks. A virtual cerebral model in this atlas has been parcellated into about 2300 components. It contains structure (Nowinski et al., 2012a), intracranial vasculature (Nowinski et al., 2011), cranial nerves and nuclei (Nowinski et al., 2012b), head muscles and glands (Nowinski et al., 2012c), and cranial nerves (Nowinski et al., 2013). The cerebral model is placed in the Talairach stereotactic coordinate system (Talairach and Tournoux, 1988) with the origin in the center of the anterior commissure on the midsagittal plane.

This work addresses the construction of the atlas of the adult human skull spatially correlated with the brain, cranial nerves, and intracranial blood vessels. In order to add the skull to the currently created atlas, a high-resolution spiral computed tomography (CT) scan of the same specimen was acquired. The skull was segmented, parcellated, and reconstructed in 3D. We modeled the complete skull with 29 bones in 3D, and spatially correlated it with the brain, cranial nerves, and intracranial vasculature.

2. Materials and Methods

The design of this skull atlas consistently follows the principles and functionality of our previously developed atlases (Nowinski, 2015b). The process of construction of the skull atlas had the following steps: CT scan acquisition, skull extraction from this scan, skull parcellation into individual bones, 3D surface modeling of the disarticulated bones, 3D model simplification (decimation), brain–skull registration, 3D surface editing of the parcellated skull, 3D surface naming and color-coding, integration of the CT-derived 3D bony models with the existing brain atlas, and validation.

2.1. Materials

A high-resolution noncontrast spiral CT scan, ranging from the cranial vertex down to the cervical vertebra C6, was acquired with 526 axial slices of 0.75 mm thickness, 0.5 mm increment, 512 × 512 matrix and $0.46875 \times 0.46875\ \text{mm}^2$ pixel size. In order to facilitate registration of the skull with the virtual brain, the same brain/head specimen was scanned.

2.2. Methods

The skull was interactively extracted from the CT scan and parcellated into individual, disarticulated bones by means of a dedicated Contour Editor described in (Nowinski et al., 2012a). This editor provides functions for fast and precise contour extraction, contour copying, editing of multiple contours while preserving the common borders between them, and synchronizing spatially the original 2D images with their orthogonal sections and reconstructed 3D models. In particular, these features were useful to handle very dentated sutures. A special care was taken to precisely extract and shape the foramina/canals and notches, as vascular and cranial nerve landmarks were used for skull–brain registration. The 3D surface cutting was helpful to edit foramina, canals, and bone sinuses from inside.

In general, generation of 3D individual skull components was carried out in a similar way as other atlas surface components reported earlier (Nowinski et al., 2012a), meaning that the iso-surfaces were extracted by means of the marching cubes algorithm (Lorensen and Cline, 1987) and the resulting iso-surface simplified depending on bone complexity and special features to be preserved (Section 4). Most of large bones were reduced by more than 20 times in the number of polygons (for instance, the frontal bone was reduced from 600,000 to 10,000 polygons); smaller bones were reduced about 10 times.

There are two approaches to a problem of skull to brain registration: (2D) scan-to-scan or (3D) model-to-model. Scan-to-scan is an automatic volume-based registration and model-to-model is an interactive landmark-based registration. Automatic MR to CT registration was attempted by employing a mutual information algorithm with the affine transformation, Mattes mutual information image metric and regular step gradient descent optimizer available in the Insight Toolkit ITK (Johnson et al., 2013). We used the code from example ImageRegistration4.cxx with the default parameters: histogram bins—24, spatial samples—10,000, max step—2.0, min step—0.001, and relaxation factor—0.8. This registration approach was not successful due to an inacceptable high inaccuracy, see the Discussion section.

Here, the skull and the brain along with the blood vessels and cranial nerves were registered interactively by employing a rigid registration (with three translations (of the smallest step of 0.02 mm) and three rotations (of the smallest step of 0.05 degree)), as the same head–brain specimen was used, based on the skull landmarks specified in Appendix B. The brain–skull transformation was determined for the complete skull to have all relevant foramina and canals (including these present at the junctions of bones).

Besides the Contour Editor, the brain atlas contains additional tools integrated with it, enabling precise editing of any imported components in the entire cerebral context, facilitated by atlas navigation (Nowinski et al., 2012a). These tools include editors for surface and tube (vessels and cranial nerves) editing as well as object coloring, grouping, and labeling. By using them, the bones were uniquely color-coded and labeled (named) based on *Terminologia Anatomica* (FCAT, 1999). Moreover, the skull anatomy index was formed and integrated with the atlas index.

The atlas content has a modular structure (Nowinski et al., 2012a) and this new content has been added into the atlas under the *Skull* module. In order to facilitate content scalability, the module matrix (containing all tissue modules) was redesigned and made extendable and scrollable with a vertical scrollbar. This solution supports displaying the existing as well as new content by appending additional buttons.

Validation (against both textual description and images) was done in terms of the skull completeness, shape of bones, course and dentation of the sutures, bone articulation as well as existence of other features, including foramina, canals, notches, fissures, ducts, processes, crests, wings, grooves for meningeal blood vessels (inner surface), grooves for dural sinuses (inner surface), impressions of cerebral gyri (inner surface), and depressions for arachnoid granulations (inner surface) based on standard textbooks (Williams