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# Morphometric analysis of the frontal sinus: application of industrial digital radiography and virtual endocast

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ABSTRACT

*Background:* The morphology and dimensions of the frontal sinus (FS) are significant in the forensic, surgical and population context.
*Purpose:* The study aimed to compare linear FS measurements taken both on radiographs and virtual endocasts and to assess the impact of the skull angulation on the FS dimensions.
*Material and Methods:* Thirteen intact dry skulls of contemporary adult males were radiographed using industrial digital radiography while they were inclined in the Frankfurt plane, through the Caldwell's view up to the Water's view by angular steps of 5°. The width and height of both frontal lobes were measured in each projection. To verify the measurements on the radiographs, ten of the skulls were μCT-scanned and virtual endocasts of the FS were generated.
*Results:* The concordance between the measurements on the virtual endocasts and the radiographs in the Caldwell's view showed almost perfect concurrence for the width (0.998) and height on the left side (0.990), and substantial one for the height on the right side (0.961). Since the width is more sensitive compared to the height, any inclination from the initial position at the Caldwell's view caused a significant distortion of the FS measurements.
*Conclusion:* The industrial μCT-systems support both 2D and 3D imaging and could generate images with a high resolution. Therefore, if the industrial digital radiography is selected as an eligible imaging modality for FS investigation and documentation in conformity with the research goals, the appropriate skull positioning ensures reliable readings of the linear FS dimensions.

## 1. Introduction

The frontal sinus (FS) is one of the four paranasal sinuses, a group of air-filled spaces developed as an expansion of the nasal cavities into the adjacent facial and skull bones. The FS begins development during the fourth fetal month, however, the pneumatization of the frontal bone initiates in the first or second postnatal year [1], while the main period of enlargement coincides with the pubertal growth spurt. Both cavities of FS develop independently due to an unequal absorption of the diploë, and as a rule their configuration is asymmetrical [2]. In adults, the FS usually appears as two irregularly-shaped cavities separated from each other by a thin bony septum and could be considerably different in shape, size and number [1–4].

The FS is considered to be unique in each person [5,6], and it remains with a stable morphology from puberty until old age when gradual pneumatisation can occur due to atrophic changes [5]. Nevertheless, the sinus morphology can be affected by a number of factors such as infections, trauma, mucocele, tumors, etc. [6]. Being an internal skull structure between the plates of the frontal bone, the sinus is well protected from injuries and taphonomic processes. Thus, due to its uniqueness, relatively constant morphology and its protected location, the FS is particularly useful for identification of human remains [7–13]. It can also be used as a feature for sex prediction [14–17]. Furthermore, the FS morphology and dimensions are essential in neurosurgical and endoscopic nasal interventions because of its proximity to the orbit and the anterior cranial base so as to avoid its injury during interventions or

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postoperative complications [4,18].

Radiological investigation is a non-invasive approach for inspection of the internal skull structures such as FS. Application of postmortem-CT for radiological identification (RADid) in the context of both single and disaster victim identifications (DVI) has already been discussed [9,19–21]. For such purposes different modalities like radiography, ultrasound, computed tomography (CT) and magnetic resonance imaging (MRI) could be used, as well as various combinations of them [19]. The reliability of inter- [12,13,22,23] and intramodality [9,11] comparisons has been tested for comparative identification using ante- and postmortem records of FS. The potential of intermodality comparisons for RADid has already been pointed out. The postmortem-CT has been compared to antemortem radiographs and vice versa [24,25], as well as MRI to CT-data [26].

The industrial CT systems are highly versatile and offer some advantages over medical CT in the postmortem examination of skeletal remains [27]. The μCT systems support a real-time X-ray inspection (industrial digital radiography, IDR), capturing and exportation of the selected projections in image file formats. The volumetric μCT imaging is a powerful tool for qualitative [28] and quantitative evaluation of bone tissue at the trabecular level by means of calculation of stereological parameters and structural anisotropy from the image datasets [29]. The obtained images are with a high resolution and allow precise metric analyses. Metric parameters of the FS have been used in elaborated identification systems based on the FS morphology [5,30] and the measurements prove to be of great value for sex differentiation [14]. However, the FS measurements have been found incomparable across different modalities e.g. radiography and cone beam CT (CBCT) [10]. In this study we aimed to perform an intermodality comparison of the linear FS measurements taken on radiographs and on volumetric images generated on industrial μCT system. Furthermore, our goals were to estimate the inherent error of the FS morphometry performed on posteroanterior (PA) radiographs, to assess the impact of the skull angulation on the FS dimensions and to establish the interval of confidence indispensable for reliable morphometric analyses of the FS on PA radiographs.

## 2. Material and Methods

### 2.1. Materials

Thirteen intact dry skulls of contemporary adult males were selected for the purposes of the study. The skulls belonged to Bulgarian soldiers who died in the wars at the beginning of the 20$^{th}$ century. Their bone remains were kept at the Military Mausoleum with Ossuary at the National Museum of Military History of Bulgaria. The age of the individuals ranged between 21–46 years and the average age was 31.6 years. In all of the investigated skulls the FSs emerge above the supraorbital line (SOL), which was considered as a baseline. The selected specimens did not feature pathologic alterations of the FS and the skull.

### 2.2. Methods

#### 2.2.1. Industrial digital radiography (IDR)

*2.2.1.1. Parameters*. The skulls were radiographed using an industrial μCT system Nikon XT H 225, manufactured by Nikon Metrology. The μCT system had a fixed X-ray source and a flat panel detector Varian 2520Dx with 1900 × 1500 pixels as the pixel size was 127 μm. It was equipped with a 5-axis manipulator allowing motion on x, y and z axis, a rotation of 360° and a tilt ranging from - 25° up to 25° utilized for the object positioning. To adjust the parameters and manage the capture of the projections the Inspect-X software was used. The settings ranged depending on the density of the specimens: voltage 104–139 kV, 106–174 μA tube current and exposure time of 500 ms. All the generated projections were saved in a Tagged Image File Format (TIFF).

**Table 1**
Description of the landmarks and measurements.

| Landmarks and measurements | Description |
|---|---|
| *Orbitale* (*o*) | The lowest point on the lower edge of the orbit |
| *Porion* (*po*) | The point located at the upper margin of the external auditory meatus |
| Supraorbital line (SOL) | The tangent line to the superior borders of the left and right orbits |
| Total width (TW) | The distance between the projected lines marking both outermost points of the frontal sinus |
| Height (Hr/l) | The distance from the baseline to the highest point of the right/left lobe of the frontal sinus |

*2.2.1.2. Positioning of the skulls*. Since the Caldwell's view (CV) provided the clearest FS silhouette and the least chance for error in the interpretation [2], it was considered a basic position (0°) in which the skulls were initially oriented without using the tilt function. In the CV the skull was inclined 20° from the Frankfurt horizontal plane (FH), one determined by both landmarks of *porion* and the left *orbitale* (Table 1). The inclination of the skull below the initial position was considered a negative value (-), whereas its lifting above it was designated as a positive value (+). To orient the skull in the CV as its basic position, the facial part of the skull had to be lifted to the appropriate angulation, and therefore the skulls were marked in advance with radiodense copper markers glued at the points determining the FH. Then the skull was placed so that the line connecting both *frontotemporale* crossed the centre of the manipulator and was with a slightly lifted facial part. Thereafter the manipulator was tilted to the position in which the markers were lined up in a row (−20°, FH). If the angulation in the initial position was not appropriate, it was corrected and the procedure was repeated. After the necessary angulation was achieved, the skull was inclined from −20° (FH) through the CV (0°) up to 25° in Waters' view (WV, 45° toward the FH) at an interval of 5° (Fig. 1).

*2.2.1.3. Imposition of the FS contours from the inclined positions*. For one of the skulls and in each of the projections, the FS contours were delineated using the Draw background curves option in the free software tpsDig, version 2.26. Each curve (sinus contour) contained 100 lengthwise located points. The x- and y- coordinates for each curve were exported as a TPS file. Then, the coordinates for the FS contours for each inclination were included in one TPS file, which was imported in the free software PAST ver 2.17c [31]. The visualization of the contours was performed using the option Landmarks in the Plot menu of the software (Fig. 2).

#### 2.2.2. Industrial μCT volumetric imaging, segmentation and generation of VE of the FS

Ten of the skulls were scanned using the same industrial μCT-system. For all of the specimens the scanning protocol was as follows: exposure time 500 ms, voltage 100 kV, power of 10 W and tube current 100 μA. A series of 2000 sequential projections was captured while the object was rotated on 360° by angular steps of 0.18°. The reconstructions were made using CT Pro 3D software and .vgl files were generated. The image resolution was 97.549 μm as the voxels were isotropic. VGStudioMax 2.2. was used for orientation of the skull in the FH using simple image registration, and also for selection and extraction of the region of interest (ROI) containing the FS lobes above the baseline (SOL). The ROIs were exported in an analyze volume (.hdr) format. The segmentation of the FS surface and 3D reconstruction of its volume, or generation of the virtual endocast (VE), were performed using the free software ITK-SNAP, version 3.6.0 [32]. The software was successfully used for ROI segmentation from volumetric medical images [33,34]. The internal surfaces of the FSs were delineated using a propagating