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The Weight of the Head and Skull, as well as The Centre of Gravity Can Be Affected by The Paranasal Sinuses

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ABSTRACT

Background: The paranasal sinuses are air-filled cavities that potentially influence the weight and center of gravity (CG) of the head and skull. Their anatomical and physiological roles warrant investigation regarding their impact on cranial biomechanics. **Objective:** to determine the effect of the paranasal sinuses on the mass and CG of the head and skull using volumetric and mass analyses from CT scans. **Patients and Methods**: a retrospective study utilizing medical records and CT scans from 130 patients (69 males, 61 females; aged 18-75) treated at Benha Medical School between January 2016 and June 2019. Participants' CT scans were analyzed using Amira software to create 3D reconstructions and simulate the presence and absence of pneumatic sinuses. Four groups were evaluated: natural pneumatic sinuses and sinuses filled with bone material for both the skull and entire head. Volumes were converted to mass estimates using established density values, and the CG was calculated for each configuration. **Results:** The mean dimensions of head and skull, along with mass and volume, revealed no significant differences when sinuses were filled with bone. The average head mass was 4.495 kg (SD 0.0736 kg), with no notable changes in CG coordinates (X: -0.370 cm ±0.08, Y: 0.094 cm ±0.13, Z: 2.66 cm ±0.79) between groups. The paranasal sinuses did not significantly alter the mass or CG of the head and skull.

Conclusion: The paranasal sinuses have a negligible impact on the mass and CG of the head and skull, suggesting their role in cranial biomechanics is minimal.

Keywords: Paranasal sinuses; Head mass; Center of gravity; CT scan; Cranial biomechanics.

INTRODUCTION

The human skull, a complex anatomical structure, plays a critical role in protecting the brain and shaping facial features. Among its many elements, the paranasal sinuses are perhaps some of the least understood in terms of their functional significance [1,2].

Traditionally, these air-filled cavities have been acknowledged primarily for their roles in reducing skull weight, humidifying and heating inspired air, and enhancing voice resonance [3]. However, recent studies have suggested that these sinuses may have additional biomechanical functions that contribute to the overall dynamics of the skull and head [4,5]. The paranasal sinuses are located around the nasal cavity and include the maxillary, frontal, ethmoid, and sphenoid sinuses. Each sinus varies in size and shape among individuals and is lined with a thin mucous membrane [6]. The evolutionary rationale behind the development of these sinuses has been debated, with theories ranging from improving vocal resonance to insulating sensitive structures like the eyes and teeth from temperature fluctuations. Despite extensive research, the contribution of these sinuses to the mass distribution and the biomechanical properties of the head remains ambiguous [3].

Studies focusing on the biomechanical impact of the sinuses have primarily concentrated on their effect on the structural integrity and stress distribution within the skull [7]. However, there is a gap in research regarding how these sinuses influence the overall mass and center of gravity of the head—an aspect crucial for understanding head movements and neck muscle workload. Given that the center of gravity affects the mechanical and physiological behavior of the head, exploring this area could provide new insights into human biomechanics [8]. Moreover, from a clinical perspective, understanding the impact of paranasal sinuses on head mass and balance can influence approaches in craniofacial surgery and rehabilitation. For instance, alterations in the sinuses due to surgical interventions or pathological conditions might affect the head's balance and necessitate adjustments in treatment plans [9]. Thus, a detailed study on this topic not only fills a scientific gap but also holds potential clinical relevance. The aim of this study was to investigate the alleged function of the paranasal sinuses in affecting the head mass and subsequently the center of gravity of the head.

PATIENTS AND METHODS

Study Design and Setting: This retrospective study was conducted using the medical records and CT scan data of patients treated at Benha Medical School between January 2016 and June 2019.

Participants:

The study population consisted of 130 individuals, with 69 males and 61 females, ranging in age from 18 to 75 years. Participants were selected based on their prior CT scans of the paranasal sinuses, which were performed for various clinical indications. Only scans of patients without pathological findings in the sinuses were included to maintain uniformity in the study sample.

Inclusion and Exclusion Criteria:

Inclusion criteria specified adults aged 18 years and older who had undergone a CT scan of the paranasal

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sinuses for reasons other than sinus pathology, and whose scans showed no abnormalities. Exclusion criteria ruled out patients with any craniofacial anomalies, previous sinus surgery, or sinus disease evident on the CT scan.

CT Imaging and Data Collection:

CT scans were reviewed and analyzed using helical scanning techniques with a slice thickness of 625 mm, operating at voltages between 120–140 kV and currents of 200–300 mA. A bone algorithm was utilized to reconstruct the raw scan data. Images and data were exported in DICOM format for further analysis.

Image Manipulation and Analysis:

Using Amira software versions 3.1.1 and 4.1.2 (Mercury-TGS, Chelmsford, MA, USA), 3D reconstructions of the cranial anatomy were created. These reconstructions enabled precise volumetric measurements of the skull and head with natural sinuses and after virtual filling of the sinuses with bone material. This manipulation simulated the hypothetical absence of pneumatic cavities to evaluate their impact on head mass and center of gravity.

Participants were divided into four groups based on the CT manipulation to simulate different states of sinus filling:

- **Group 1:** Skull with natural pneumatic sinuses.
- **Group 2:** Skull with sinuses virtually filled with bone material.
- **Group 3:** Entire head including natural pneumatic sinuses.
- **Group 4:** Entire head with sinuses virtually filled with bone material.

Calculation of Mass and Center of Gravity:

Volumes derived from CT scans were converted to mass estimates by applying density values—1.036 g/cm³ for brain tissue, and adjusted values for bone and soft tissues based on literature and empirical data. [7]. The centre of gravity for each configuration (with and without filled sinuses) was calculated using formulas integrating mass distribution across the different cranial components.

The mean dimensions of head and skull are shown in **Table 1**.

Table 1: Mean Dimensions of Head and Skull

Dimension 130 patients	Part	Mean (cm)	Standard Deviation (SD)
Breadth	Head	15.65	0.41
	Skull	14.2	0.72
Length	Head	18.5	0.69
	Skull	17.4	0.45
Circumference	Head	55.9	1.49
	Skull	48.8	0.76

Mass, volume, and density of skull and head are shown in **Table 2**.

Table 2: Mass, Volume, and Density of Skull and Head

Part	Mean Mass (kg)	SD (Mass)	Mean Volume (cc)	SD (Volume)	Density (kg/cc)
Skull	2.32	0.53	1562	0.54	1.131
Head	4.49	0.35	4082	0.13	1.107

To convert volumes to masses, volume (cm³) was multiplied by density (g/cm³). Ignoring the thin sinus epithelium, the air sinus density was taken as zero, as was the resulting mass. The human head contains the brain, which weighs about 1.3 kg, the skull, eyes, teeth, facial muscles, and skin. Overall, an adult head weighs around 4.5 to 5 kg. The entire head can be approximated to a sphere with a 100 mm radius. Skull volume includes the volume of intraosseous sinuses. The volume of a sphere is $(4/3)\,\pi r^3$. The approximate volume of the head is 4 liters or slightly more, depending on age and gender. [9].

Bone density was determined using previous calculations and computer simulations. To achieve this, the "Rotate" application in the software must be operated along the inertial axis with the pivot point set at the mass center. From this analysis, the coordinates in each of the three planes (axial, coronal, and sagittal) can be determined [9].

Ethical considerations:

The study was done after being accepted by the Research Ethics Committee, Benha University. All patients provided written informed consent for the publication of their data in a scientific study, ensuring protection of their confidentiality and privacy. This work has been carried out in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki) for studies involving humans.

Statistical Analysis

Data management and statistical analysis were done using SPSS version 26 (IBM, Armonk, New York, United States). Descriptive statistics (mean, standard deviation) were used to summarize the dimensions, mass, and center of gravity of the head and skull in each group. Comparative analyses were performed using t-tests to determine the significance of differences in mass and center of gravity between the different head and skull configurations (P value < 0.05 was considered significant).

RESULTS

Regardless of gender or age, the findings from 130 respondents were gathered, and the mean and standard deviation were determined. Instead of merely estimating head mass, the contribution of pneumaticity to total head mass (and hence any weight reduction) was calculated by treating the paranasal sinuses as bone and assigning the sinus volumes the density of bone. The greatest recorded value of any of these measures was used to calculate the length, weight, and circumference.

The weights of skull and brain tissue types in the human head are shown in **Table 3**.

Table 3: Weights of Skull and Brain Tissue Types in the Human Head

Segment	Density (kg/cm^3)	Volume (cm^3)	Weight (kg)
Skull	1.13	1562	2.32
Brain	1.040	1474	1.532

The weights of each of the three tissue types in the human head are shown in **Table 4**.

Table 4: Weights of Each of the Three Tissue Types in the Human Head

Segment	Density (kg/cm^3)	Volume (cm^3)	Weight (kg)
Soft Tissue	1.060	711.5	0.7541

Volumes, tissue densities, and masses for skull of human under two different states of pneumaticity are illustrated in **Table 5**.

Table 5: Volumes, Tissue Densities, and Masses for Skull of Human Under Two Different States of Pneumaticity

Component	Measurement	Group 1: Skull with All Pneumatic Sinuses		Group 2: Skull without Paranasal Sinuses (Bone Inserted)	
		Volume (cm^3) Mean ± SD	Mass (g)	Volume (cm^3) Mean ± SD	Mass (g)
Skull		1561 ± 7.3	2327	1562 ± 7.3	2327
Maxillary Sinus		19.5 ± 6.4	0.0	19.4 ± 6.4	21.9
Frontal Sinus		6.2 ± 4.2	0.0	6.1 ± 4.2	6.82
Sphenoid Sinus		7.1 ± 3.7	0.0	7.2 ± 3.7	7.81
Ethmoidal Sinuses		5.9 ± 3.9	0.0	5.91± 3.9	6.49
Total Sinuses	Both sides	76.4 ± 17.6	0.0	76.42 ± 17.6	85.04
Density (kg/cm^3)		1.1		1.11	

Volumes, tissue densities, and masses for head with and without paranasal sinuses are detailed in **Table 6**.

Table 6: Volumes, Tissue Densities, and Masses for Head with and without Paranasal Sinuses

Component	Measurement	Group 3 (With Sinuses)		Group 4 (Sinuses Replaced)	
		Volume (cm^3)	Mass (g)	Volume (cm^3)	Mass (g)
Head		4082 ± 0.73	4490	4082 ± 0.734	4575.04
Maxillary Sinus		19.5 ± 6.4	0.0	19.5 ± 6.42	21.45
Frontal Sinus		6.2 ± 4.2	0.0	6.22 ± 4.2	6.82
Sphenoid Sinus		7.1 ± 3.7	0.0	7.11 ± 3.7	7.81
Ethmoidal Sinuses		5.9 ± 3.9	0.0	5.91 ± 3.9	9.05
Total Sinuses	Both sides	76.4 ± 17.6	0.0	76.41 ± 17.6	85.04
Density (kg/cm^3)		1.107		1.1	

Comparative mass of skull and head with paranasal sinuses (air-filled vs. converted to bone) are provided in **Table 7**.

Table 7: Comparative Mass of Skull and Head with Paranasal Sinuses Air-filled vs. Converted to Bone

Description	Condition	Mass (g)
Skull Mass	With paranasal sinuses converted to bone	2405
	With paranasal sinuses air-filled	2320
Head Mass	With paranasal sinuses converted to bone	4575
	With paranasal sinuses air-filled	4490

For the head and skull, we analyzed, the center of gravity, which is located approximately 2.4 cm forward and 2.6 cm above the atlantooccipital joint. [8].

Coordinates for center of gravity in the Frankfort plane for each head and skull type are provided in **Table 8**. The average weight of the subject's head was determined to be 4.495 kg with a standard deviation of 0.0736 kg. The average coordinates for the center of gravity (CG) of the head were 0.37 cm (±0.08) on the x-axis, 0.07 cm (±0.13 cm) on the y-axis, and 2.48 cm (±0.79 cm) on the z-axis. Overall, no significant differences were observed in any of the parameters, including mass or center of gravity, when the paranasal sinuses were filled with bone. Therefore, the paranasal sinuses did not significantly affect either the mass or the center of gravity of the head and skull.

Table 8: Coordinates for Center of Gravity in the Frankfort Plane for Each Head and Skull Type

Description	Group 1 Skull (cm)	Group 2 Head (cm)	Group 3 Skull with Bone instead of PNS (cm)	Group 4 Head with Bone instead of PNS (cm)
X-Axis (cm)	0.3	0.37	0.35	0.06
Y-Axis (cm)	0.12	0.07	0.12	0.08
Z-Axis (cm)	2.7	2.48	2.83	2.78

DISCUSSION

In the current study, the mean head dimensions in cm and standard deviation for length, breadth, and circumference were 18.5 ± 0.69 cm, 15.65 ± 0.41 cm, and 55.9 ± 1.49 cm, respectively, for the skull the dimensions were 17.4 ± 0.45 cm, 14.2 ± 0.72 cm, and 48.8 ± 0.76 cm. These results are consistent with **Clauser *et al.*** [10] and **Ching** [11]. However, the head volume, mass, and density were 4.49 ± 0.35 kg, 4082 ± 0.13 cc, and 1.107 g/cc respectively, and for the skull, they were 2.32 ± 0.53 kg, 1562 ± 0.54 cc, and 1.131 g/cc. In another study, **Kruggel** used MRI to separate the head components, considering gender and age rather than using CT scans [12]. **Makris *et al***. estimated each of the head part volumes using MRI as well. Our results were consistent with their estimated cranial cavity volume [13].

In our study, the volume of the maxillary sinuses was 19.5 cc, the frontal sinus was 6.2 cc, the sphenoid sinus was 7.1 cc, and the ethmoid sinuses were 5.9 cc. The total volume of the bilateral paranasal sinuses was 76.4 cc, which is consistent with results from previous studies [14,15].

Even today, the volume of air cavities in the paranasal sinuses is not only the simplest but also the most essential criterion used in paranasal sinus examination. [11]. The study used three-dimensional (3-D) computed tomography (CT) data to recreate the dimensions of the paranasal cavities in 20 healthy adults. To eliminate any bias in calculating the cavity boundary, we used silicone injection and 3-D reconstruction to measure the bilateral maxillary sinuses of a macaque. The CT value for 3-D reconstruction was then calculated by comparing the volume measured by direct injection to the CT value. The healthy subjects' sinuses were then assessed using 3-D reconstruction imaging. Individually and collectively, the paranasal sinuses appeared to be larger than previously reported: 90.1 ml in males and 72.5 ml in females, on average. When compared to other body size indices, the increase in size was rather noticeable, and the lower prevalence of sinusitis was thought to have a part in the present Japanese population's increased volume of paranasal sinuses [14]. The mean volumes (± SD) of unilateral sinuses were 6.0 ± 4.3, 19.1 ± 6.1, 5.7 ± 1.5, and 7.1 ± 3.9 cm^3 for the frontal, maxillary, ethmoidal, and sphenoidal sinuses, respectively. The volumes of paranasal sinuses were significantly different between the sexes ($P < 0.05$). There was no statistically significant difference between the right and left sinuses. However, the volume of paranasal sinuses gradually decreased after the third decade [15].

Volume (cm^3) was multiplied by density (g/cm^3) to convert volumes to masses. The density of bone in our study was calculated to be 1.1 g/cm^3 each tissue type was allocated a specific density based on literature values [16-17].

The average weight of the subject's head was 4.495 kg, with a standard deviation of 0.0736 kg. The center of gravity (CG) of the head had average coordinates of 0.37 cm (±0.08) on the x-axis, 0.07 cm (±0.13) on the y-axis, and 2.48 cm (±0.79) on the z-axis. Despite filling the paranasal sinuses with bone, there was no significant difference in any parameters, such as mass or center of gravity. Remarkably, the head maintains the same center of gravity regardless of whether the skull contains tissues or lacks paranasal sinuses. This finding is supported by numerous studies. [16]. However, crash test lab researchers have spent years developing intricate preparations and methodologies to determine the center of gravity of cadaver heads. [16].

Beier *et al.* (1980) estimated the average center of gravity for several dozen cadaver heads in a report presented to the Office of Naval Research [18]. They discovered the average placement along the mid-sagittal plane, "0.8 cm in front of the auditory meatuses and 3.1 cm above the Frankfurt plane". This location corresponds to the midline of the skull, roughly an inch forward from the atlantooccipital joint and an inch above in layman's terms, positioned over the sella turcica [18].

To validate this new method, researchers compared the obtained mass properties to those derived from medical images for 15 human cadaver heads. The study included seven female and eight male unembalmed human cadaver heads, aged 16 to 97 (mean age = 59.22). Mechanical measurements were taken of specimen weight, center of gravity (CG), and major moments of inertia [19].

Computerized Tomography (CT) data was used to calculate mass properties, dividing the data into three tissue types: brain, bone, and skin. The center of gravity (CG) for the three tissue types was consistently located in each case. The CG of the soft tissue was superior to the origin, anterior, and inferior to the CG of the bone and brain. Weight, CG, and moments of inertia (MOIs) were calculated using binary volumetric data analysis. When medical image data were matched to mechanically measured data, inaccuracies occurred as follows: Weight discrepancies ranged from 0.4% to 6% (mean = 2.8%), CG discrepancies ranged from 0.01 cm to 0.34 cm (mean = 0.1 cm), and MOIs discrepancies ranged from 0.1% to 10.4% (mean = 5.2%). Weight computations in medical images showed a substantial positive bias ($p = 0.0074$), as did two of the three MOIs (Ixx: $p = 0.0074$, Iyy: $p = 0.0010$). The use of medical imaging analysis to calculate human head mass properties proved to be a reliable and accurate non-invasive method [10].

According to the data, 3D modeling appears to be a reliable method for determining the weight and center of gravity of the human skull. The largest weight divergence was only 8.6 cm, while the largest CGz discrepancy was 0.83 cm. These differences were not significant ($p = 0.05$), according to t-test results [19]. Compared to earlier studies, [16]. the results of 3D analysis reveal that our data is accurate and nearly identical.

One of the primary limitations of this study is its retrospective design, which inherently relies on previously collected data and may not account for all potential confounding variables. The sample was restricted to patients with no sinus pathology, potentially limiting the generalizability of the findings to populations with varying sinus conditions. Additionally, the use of virtual models to simulate filled sinuses may not perfectly replicate the physiological properties of actual bone, which could affect the accuracy of the results regarding mass and center of gravity calculations. Lastly, the study did not account for individual variations in bone density and tissue composition, which could influence the study's outcomes. These factors suggest caution in extending these results to broader clinical or biomechanical applications without further prospective and controlled studies.

CONCLUSION

The mass and center of gravity of the skull are unaffected by the pneumatization of the paranasal sinuses. The CG for the three tissue types was consistently located in each case. The center of gravity of the skull remains constant regardless of the state of the skull (bone only, tissue-covered, and all sinuses filled with bone), implying that the paranasal sinuses have no bearing on the head's center of gravity. The unique position and shape of the paranasal sinuses is the keystone of this phenomenon. As a result, further research is needed to enhance our understanding of human biomechanical and biophysical responses.

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