DERLEME REVIEW

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Historical Development of Skull Thickness Measurements and Usability of These Measurements in Forensic Medicine: A Traditional Literature Review

Kafatası Kalınlığı Ölçümlerinin Tarihsel Gelişimi ve Bu Ölçümlerin Adli Tıpta Kullanılabilirliği: Geleneksel Bir Literatür Taraması

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ABSTRACT For approximately 2 centuries, the estimation of ancestry, sex, and age from skull measurements has been one of the issues of anthropology. Since the first studies of skull thickness in 1879, measurements were first made with calipers, and then with technological developments over time are also now made with X-rays, computed tomography examinations, ultrasound and magnetic resonance imaging. Skull thickness was used for several clinical purposes in medicine, such as determining the most suitable area for bone grafts, deciding on the appropriate area in the temporal bone for hearing aid application, monitoring changes in bone thickness in various diseases and treatments, etc. It has also been used for forensic identification, and to explain the mechanism of skull fractures in forensic medicine, although it was described in a limited number of articles. The aim of this study is to make a detailed literature review of the historical development of skull thickness measurement techniques, including the use of skull thickness measurements in forensic identification and skull fracture mechanism. It can be foreseen that skull thickness will be an indispensable part of forensic identification, especially in skeletons, together with the mapping method, an example of which has been carried out. Likewise, there is no doubt that measuring the thickness of the regions where the fracture lines pass in the skulls and the bone density of these regions by scintigraphy and combining them with the 3D Finite Element Model will lead to new ideas about the mechanism of fracture formation.

Keywords: Skull thickness; forensic identification; X-ray; computed tomography; ultrasonography

ÖZET Yaklaşık 2 yüzyıldır kafatası ölçümlerinden; soy, cinsiyet ve yaş tahmini, antropolojinin konularından biri olmuştur. 1879 yılındaki kafatası kalınlığı üzerine gerçekleştirilen ilk çalışmalardan bu yana önce kumpas yardımı ile ölçümler yapılmış, daha sonraki zamanlarda teknolojinin gelişmesi ile birlikte X ışını, bilgisayarlı tomografi, ultrasonografi ve manyetik rezonans görüntüleme gibi radyolojik teknikler de kullanılmaya başlanmıştır. Kafatası kalınlığı; tıpta kemik greftleri alımı için en uygun alanın belirlenmesi, işitme cihazı uygulanması için temporal kemikteki en uygun alana karar verilmesi, çeşitli hastalık ve tedavilerde kemik kalınlığındaki değişikliklerin izlenmesi gibi çeşitli klinik amaçlar için kullanılmıştır. Ayrıca sınırlı sayıda makalede tanımlanmış da olsa adli tıpta adli kimlik tespiti ve kafatası kırıklarının mekanizmasını açıklamak için de kullanılmıştır. Bu çalışmanın amacı, kafatası kalınlığı ölçümlerinin adli kimliklendirme ve kafatası kırılma mekanizmasında kullanımı da dâhil olmak üzere kafatası kalınlığı ölçüm tekniklerinin tarihsel gelişimi hakkında ayrıntılı bir literatür taraması yapmaktır. Özellikle iskelet formunda bulunan cesetlerde, yakın bir gelecekte kafatası kalınlıklarının, bir örneği gerçekleştirilmiş olan haritalama metodu ile birlikte adli kimlik tespitinin vazgeçilmez bir parçası olacağı öngörülebilir. Aynı şekilde, kafataslarındaki lineer kırıkların geçtiği bölgelerin kalınlıklarının ve bu bölgelerin kemik yoğunluğunun sintigrafiyle ölçülmesi ve bunun 3D Finite Element Model ile birleştirilmesinin, kırığın oluşum mekanizması hakkında bugüne kadar tanımlananların ötesinde yeni fikirlere yol açacağından şüphe yoktur.

Anahtar Kelimeler: Kafatası kalınlığı; adli kimliklendirme; X ışını; bilgisayarlı tomografi; ultrasonografi

For approximately 2 centuries, the estimation of ancestry, sex, and age from skull measurements has been one of the issues of anthropology. The book published by Krause in 1879 provides the first known detailed definition in literature of skull measurements (as height of the whole head-front side, height of the

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whole head-back, length of the skull from the forehead to the occiput, width of skull-parietal diameter, width of skull-temporal diameter, horizontal circumference of the skull, height of the face from the bridge of the nose to the chin, width between the cheeks, width in front of the ears and thickness from the tip of the nose to the ear).[1] In the following years, skull thicknesses were used for several medical purposes, such as determining the most suitable area for bone grafts, deciding on the appropriate area in the temporal bone for hearing aid application, following the bone changes of patients with skeletal Class II and Class III malocclusions or skeletal deep bite, monitoring patients with spontaneous cerebrospinal fluid leakage, investigating the effects of bone thickness on electroencephalography, tracking the changes in bone thickness increase in patients with severe blood dyscrasias and hyperplasia of the red marrow, and investigating the relationship between epilepsy and dolantin therapy.[2-15]

Skull thickness has also been used for forensic identification and in forensic medicine. Several studies have reported the use of skull thickness for the determination of ancestry, sex, age, and the comparison of bony details.[16-35] Moreover, these values have been evaluated in terms of the mechanisms of skull fracture formation in several studies.[36-47]

The aim of this study was to make a detailed literature review of the historical development of skull thickness measurement techniques, including the use of skull thickness measurements in forensic identification and skull fracture mechanism.

THE HISTORICAL DEVELOPMENT OF SKULL THICKNESS MEASUREMENT TECHNIQUES

In the 19th century, various measurements and definitions were made on the skull. Although these measurements did not initially include skull thickness, the definitions included thicknesses in various regions of the skull.[1,48-54] The first known definition of skull thickness in the literature was made by Kraus in 1879.[1] The first known detailed study of skull thickness in the literature was reported in 1882 by Anderson, who took measurements at 11 points with calipers on 154 cadaver skulls and recorded frontal eminence and the weight of the brain.[54] Although no relationship was found between the weight of the brain and the thickness of the skull, he suggested that this would not affect the view that the skull thickens when the brain shrinks. Measurements of the thickness of 445 dry skulls were taken by Todd in 1924 using calipers.[16] He stated that cranial thickness increased slightly until about sixty years of age, but there was no evidence of any change later, and it was not possible to determine the actual thickness because cranial thickness was related to many variables, and cranial thickness was related to skull type and scalp thickness.

In 1941, Twiesselmann took measurements at 12 points on the dry skulls of 200 Parisians and 200 Brussels residents and defined skull thicknesses and compared them with each other.[55]

In 1966, Hansman measured the interorbital distances and skull thickness in the lambda, from anteroposterior (AP) and lateral skull X-rays of individuals aged between 0 and 25 years to establish percentile standards to help determine the growth process in children.[18]

In 1979, Ivanhoe measured human skull thickness on temporal squamas, cerebellar fossas, zygomatic arches, frontal bosses, midfrontal, bregma, parietal bosses, obelion, lambda, pterion, asterion and cerebral fossas in some northern hemisphere populations directly with osteometric calipers.[56]

In 1985, Pensler and McCarthy measured skull thickness at selected points in 200 fresh adult cadavers for the determination of potential calvarial donor sites.[5]

With the aim of determining appropriate calvarial graft donor sites in 1989, Sullivan and Smith measured skull thickness with calipers (1) 3 cm lateral from the sagittal midline and 2 cm posterior to the coronal suture, and (2) in the midline 2 cm inferior to the lambdoidal suture.[57]

In 1990, Ishida and Dodo measured skull thickness on the frontal eminence (left-right), parietal eminence (left-right), bregma and lambda of the skulls of 105 males and 47 females ranging in age from 17 to 90 years.[58] The results were compared with those from the Neolithic Jomon series (35 males, 20 females).

In 1997, Hwang et al. measured the thickness of 88 parietal bones of 44 people using calipers in order to find the most suitable area for bone grafts from the parietal bone.[2] The thickness of the posteromedial region of the parietal bone, which is the thickest part close to the lambda, was found to be on average 6.67 mm, and the thickness of the thinnest part towards the anterolateral direction was 4.73 mm on average.

In 2003, Jung et al. measured the regional thickness of the parietal bone using calipers on 47 Korean adult skulls to clarify the clinical use of parietal bone graft in maxillofacial reconstruction.[4]

One of the most comprehensive studies in this field was conducted by Moreira-Gonzalez et al. in 2006.[20] They performed measurements at a total of 40 points with digital calipers on the frontal, occipital and parietal bones in the calvaria of 281 skulls. The average thickness of the skull was found to be 6.32 mm (minimum 5.3 mm maximum 7.5 mm), a statistically significant increase in thickness was observed towards the posterior parietal bones, and the change was not related to age. In addition, the thickest area of the skull was found to be the parasagittal posterior parietal area in male skulls and the posterior parietal region in the middle of the sagittal and superior temporal lines in female skulls. Moreira-Gonzalez et al. stated that the differences between male and female skulls reached greater values towards the back of the parietal bones.[20]

BEGINNING TO USE RADIOLOGICAL TECHNIQUES IN MEASUREMENT OF SKULL THICKNESS

Although skull thickness measurements were initially made using calipers on dry skulls, radiological studies have also been used in this area since the 1930s. In 1931, Broadbent developed the roentgenographic technique (Bolton-Broadbent technique) in order to take cephalometric measurements for orthodontic purposes in living people.[59] Broadbent suggested the possibility of making accurate determinations of changes in the living head that may be due to developmental growth using a standardized roentgenographic technique. This improved roentgenographic technique allowed the visualisation of craniometric landmarks of the face and the cranial base of a living person. This craniometric technique had the decided advantage of not having to determine the areas in the cranial base that show no change between certain ages seen in roentgenograms, thereby providing a very accurate method of measuring changes in the teeth, jaws and face.

In 1953, Roche who was inspired by Broadbent's technique, measured skull thickness on the midway between nasion and on the bregma, and on the nasion, vertex, lambda and euryon.[17] This study was planned as a cross-sectional study, and a total of 32 white American children, 14 boys and 18 girls, who participated in the study, were X-rayed at 3-month intervals in the first year, at 6-month intervals between the ages of 1-5 and annually until the age of 21. These radiographs were all taken under standardized conditions using the Bolton-Broadbent cephalometer and the measurements made on them had all been corrected for the known expansion amount equal to the measurements obtained from dry skulls.

In an extensive radiological study in 1975 by Adeloye et al., skull thickness was examined with measurements 3 cm in front of the coronal suture, 3 cm behind the coronal suture, 3 cm above the lambdoid suture and 3 cm below the lambdoid suture on normal plain skull radiographs of 300 black and 200 white Americans.[19] It was stated that "both races had a rapid increase in skull thickness in the first two decades of life. Subsequently, a small increase was observed, with a peak between the ages of 50 and 60 years. Sex differences varied, but females in both races in certain age groups had significantly thicker parietal and occipital bones than males. The frontal bone was thicker in white men than in blacks, and the parieto-occipital bone was thicker in blacks than in whites".

In 1988, Letts et al. reported that the skull thickness measured by computed tomography (CT) scan in children under the age of 6 years ranged from 1.1 mm to 4.3 mm.[60]

In 1994, Koenig et al. measured skull thickness (on two-thirds of the distance from the external auditory meatus to the sagittal suture) on the cranial CTs of 96 patients aged 0-21 years to determine the appropriate bone graft donor area in children.[61] They stated that the growth velocity of increasing thickness of the parietal bone decreased with increasing age.

Studies on bone thickness measurements with CT were previously aimed at measuring the cortical layers of bones other than the skull, such as the femur, radius, and vertebrae.[62] In 1998, Newman et al. stated that for CT studies, the thickness and density of a thin structure will depend on the accuracy of the CT measurement, spatial resolution and pixel size.[62] It was also stated that the non-homogenous nature of the bone and surrounding structures with different CT numbers were obstacles to accurate measurement of skull thickness measurements. In 1999, Prevrhal et al., stated that a definition below the level of 10% change in cortical width was unsatisfactory in bones with a cortical shell thinner than 1.2 mm.[63] They determined that changes in cortical thickness can only be evaluated if the change is very large or if the measured bone is of sufficient thickness. In a study by Dougherty and Newman in that same year, the imaging process was simulated by combining experimentally determined point spread functions with rectangular and Gaussian profiles, for various field of view or pixel sizes and reconstruction kernels.[36] The simulations successfully explained the reported overestimation of thickness and underestimation of density when imaging thin structures. Dougherty and Newman suggested that the average value of the peak CT numbers measured along the medial axis of the cortical shell be adopted as an index of cortical shell strength for circumventing some difficulties.[36]

Tellioğlu et al. measured skull thickness with CT in 2001 to determine the best bone graft donor site from the skull.[3] Measurements were taken on 33 right and 31 left parietal bones with micrometer and CT from five points on each, and the micrometer and CT measurements were determined to be compatible. The X-shaped area where the cranial thickness was measured was located 3 cm lateral of the junction between the anterior two-thirds of the sagittal suture and the posterior third, and 5 measurements were taken from the anterior and posterior ends of this X and its center. In the first known skull measurements made with CT, the mean thickness of the right parietal bone (n=33) was measured as 5.66±1.28 mm with the micrometer and as 5.80±1.32 mm with CT. The mean thickness of the left parietal bone (n=31) was measured as 5.83±1.15 mm with a micrometer and as 6.10±1.13 mm with CT.

In 2001, Ruan and Prasad developed four detailed head models for finite element analysis, based on ultrasound (US) measurement of seven skull specimens and previous data reported in the literature.[37]

In 2003, Prevrhal et al. stated that accuracy errors in CT-based cortical thickness measurements can be well resolved with computer models containing limited in-plane and inter-plane resolution effects.[64] It was reported that there were some errors in the measurement of cortical thickness in the spine for it had lower true cortical thickness; whilst accurate cortical thickness measurement in the femoral neck could be achieved due to a thicker cortical shell.

In 2004, Deck et al. presented an improved head 3D Finite Element Model (FEM) with a detailed skull geometry, including skull thickness variation and anatomically reinforced beams.[41] In 2006, Raul et al. defined the use of an adult FEM of the head, namely, the ULP model, to study the consequence of two fall scenarios.[42] This model was developed in 2008, taking into account the different thickness of the skull and thereby providing the possibility of studying the consequence of head impacts and allowing skull fractures to be predicted with greater accuracy.[44]

In 2006, Stölzel et al. measured the thickness of the temporal bone behind the auricle using both CT and US in order to find the most suitable area to place a hearing aid, and it was reported that the mean bone thickness was 5.2 mm on CT and 4.2 mm on US.[6]

In 2007, Li et al. analyzed the AP length and width of the skull of 3,000 living people and the thickness of the frontal, parietal and occipital bones on CT at 10 points.[32] The mean thicknesses of the frontal, parietal and occipital bones were determined to be 6.58 mm, 5.37 mm and 7.56 mm in males, and 7.48 mm, 5.58 mm, and 8.17 mm in females, respectively.

In 2008, Chompoopongkasem et al. measured thickness in 65 adult Thai cadaver skulls aged >20 years (34 male and 31 female) using a micrometer and three-dimensional CT in order to determine the optimal donor area for bone grafting.[65] These measurements were taken from a total of 18 points (9 right side, 9 left side) in the parietal bone, and the thickness of all parietal bones was reported to be 6.68 mm. In that study, it was concluded that the results of measurements made on three-dimensional CT were acceptable and compatible with the results of measurements taken with a micrometer.

In the same year, Hatipoglu et al. stated that determining the sex, body mass, and age from the skull of a person was of critical importance in forensic medicine and anthropology.[21] A total of 179 skulls of cases aged 4-85 years were examined using magnetic resonance imaging to investigate whether there is a relationship between the measurements (diploeic bone thicknesses measured from glabella, bregma, lambda, opisthocranion and euryon regions and lengths of glabella-opisthocranion, vertex-basion, euryon- euryon, basion-opisthion) and the characteristics of the person (sex, age and body mass index).

In 2009, Tretbar et al. determined the skull thickness with two consecutive caliper measurements at 3 different points on 16 human skulls kept in formaldehyde, then repeated these measurements with 3 different ultrasonography (USG) methods from the same points.[66] It was stated that the measurements of skull bone thickness are feasible with A-mode USG using the SonoPointer.

In 2010, Federspil et al. measured the thickness of 28 adult cadaver temporoparietal bones kept in formaldehyde using calipers, CT and SonoPointer USG for screening before hearing aid application.[7] These measurements were applied at a point (BAHA point) on the temporoparietal bone located 55 mm from the center of the outer ear canal, and 30 mm above the horizontal plane as defined by the zygomatic process. The average thickness at the BAHA point was measured as 6.0 mm (SD, 1.9 mm) with calipers. The measurements obtained with CT were differed by 0.05 mm from the measurements with calipers, and the measurements obtained with SonoPointer USG differed by 0.3 mm from the measurements with calipers.

In 2015, Delye et al. conducted a pilot study with 3D FEM of 187 patients aged 0-20 years, with the aim of creating a normative database for age-specific 3D geometric data, bone density and bone thickness of the developing skull.[47] Although the aim was to provide automatic definition of patient-specific normative target values with this database and to generate data for objective long-term follow-up in craniosynostosis surgery, the future use of this database in forensic identification cannot be ignored.

In 2020, Domenech-Fernandez et al. measured the skull thickness at 8 points on CTs of 139 children aged 0-17 years in order to determine the appropriate point for secure pin placement in halo fixation.[26] It was stated that from birth to skeletal maturity, left lateral thickness increased significantly less, compared with antero-lateral, posterior, postero-lateral and midline anterior thicknesses. At the end of growth, the thickest and thinnest points of the vault (absolute value) were found at the posterior, and right and left lateral measurement sites, respectively. Children aged <4 years exhibited the highest variability in anterolateral and posterolateral skull bone thickness, with thickness <3 mm observed in 85% and 92% of cases, respectively.

STUDIES TO INVESTIGATE THE RELATIONSHIP BETWEEN SKULL FRACTURES AND SKULL THICKNESS

In 1970, Hodgson et al. investigated the fracture behavior of the frontal bone of the skull against cylindrical body surfaces.[40]

In 1982, Got et al., examined 146 cadaver skulls and revealed the dominant effects of skull thickness and mineralization on fracture formation.[39]

In 1993, Law examined more than 20 samples taken from a dry skull by piercing at 27 points.[43] Law suggested that the presence and absence of cancellous bone affects bone resistance. Temporal bone samples without a cancellous layer have higher resistance values, although they are among the thinnest samples, and the absence of cancellous bone significantly increases resistance compared to bone samples with a cancellous bone layer. Law stated that "there is an increase in both the compact and cancellous tissue of the bone as the thickness of the skull increases, and the resistance is less in thicker skulls due to the rate of relative increase in the cancellous tissue".

In their work with US measurement in 2001, Ruan and Prasad reported fracture mechanism.[37] Several forehead impacts were simulated to assess the effect of skull thickness on skull and brain responses, then skull and brain iso-stress curves were created to examine the threshold of skull fracture and reversible concussion, and the results of the models were compared with existing skull fracture data. As the skull thickness increases, there is an increasing protective effect for the skull and the brain. This increase in protection was found to be more pronounced for skull fracture than for reversible jolting, which shows asymptotic behavior. When the asymptotic behavior of the skull and brain iso-stress curves between 8 and 9 ms was multiplied, it was seen that the threshold of skull fracture increased with decreasing duration of strokes regardless of skull thickness, and similarly, the concussion threshold increased with a shorter duration of action.

In 2007, Delye et al. investigated whether an energy failure level applies to skull fracture mechanics in 18 unembalmed post-mortem human heads under dynamic frontal loading conditions.[38] There was shown to be a significant correlation between the apical strength of the skull at the onset of fracture and the bone thickness of the object's impact site.

In 2009, Mahinda and Murthy measured skull thickness from 10 points in 76 autopsy cases.[34] The importance was emphasized of skull thickness in the development of skull fractures and intracranial hemorrhage, but it was also stated that this should be confirmed by future studies.

In the same year, Raymond et al. examined 7 unembalmed skulls, and stated that the thickness of the scalp and skull, as well as the kinetic energy of the impacted object, played a role in the formation of skull fracture.[45]

From the study of a model in 2013, Hamel et al. revealed that impact velocity and surface, and skull cortical thickness and density were effective factors in the occurrence of skull fractures.[46]

STUDIES ON THE USABILITY OF SKULL THICKNESSES IN PERSONAL IDENTIFICATION

In 1998, Ross et al. measured a total of 165 autopsy specimens, 58 females and 122 males, but no conclusions could be drawn to support previous studies of increased head thickness with age, except those associated with hyperostosis frontalis interna.[30] They observed different trends in skull thickness in females and males. Skull thickness in females, particularly in the frontal region, showed a steady increase with age and a sudden increase around 65 years of age, while in males a steady decrease with age was seen. They stated that future research on skull thickness will broaden the knowledge of human variation and may be useful in forensic practice.

In 2011, Novakovic et al. measured the temporal bone thickness of 195 adults on 100 CT scans to determine bone thickness in hearing aid surgery.[8] Cranial thickness was greater in males at the level of the external auditory canal and at 1 cm above, whereas it was significantly greater in females than males at 5 cm above the external auditory canal level.

In 2012, Smith et al. described an automated analysis for measuring skull thickness and density on CT in 300 patients aged between 0 and 18 years.[22] With this method, it was observed that both bone thickness and density increased with age.

In 2014, Baral et al. measured skull thickness from 9 points in the frontal, parietal and occipital bones with CT in 100 people aged >20 years.[23] Average bone thicknesses were 5.8 mm in the frontal bone, 5.4 mm in the parietal bone and 8.6 mm in the occipital bone, with no difference detected between the right and left sides, and genders.

In the same year, Voie et al. collected the CT scans of calvaria from 51 human corpses.[67] These were analyzed in silico using more than 2,000 measurement sites per skull. In these areas, individual and combined thickness and density calculations were made for the three skull layers, and the skull surfaces were mapped parametrically. It was stated that the density and thickness vary widely over the skull surface of a person and different persons, and it was suggested that the spatial distribution of skull thickness and density could create a unique pattern for each skull. Finally, the parametric mapping of the skull measurements was reported to be individual unique identifiers.

In 2018, Farzana et al. measured skull thicknesses at 9 points on the cranial CT scans of 52 males and 52 females, and found no difference in frontal bone thickness between the 2 sexes.[35] However, it was stated that the posterior parietal bone and the anterior and middle occipital bone were significantly thicker in females than males.

In a study conducted in Nepal by Thulung et al. in 2019, skull thicknesses at 4 points were measured with CT in 100 people (51 males, 49 females; 57 Caucasian, 43 Mongolian) aged 15-50 years.[25] The results of that study showed no significant difference between the sexes or ethnic groups in terms of skull thickness.

CONCLUSION

In this review, it was seen that the skull thickness values serve many clinical purposes, such as determining the most suitable bone graft donor site on the skull, finding the most appropriate location where hearing aids could be placed, monitoring various diseases, and following some diagnostic and treatment methods.

However, only a few studies were available of skull thickness for forensic medicine purposes.

Despite the initial drawbacks of measurements with CT and USG, technological advances have overcome most of the handicaps in these modalities. Such methods will allow for skull thickness measurements in future, more extensive series.

It can be predicted that in the very near future, skull thickness will be an indispensable part of forensic identification, especially in corpses found in skeletal form. Likewise, there is no doubt that measuring the thickness of the regions where the fracture lines pass in the skulls and the bone density of these regions by scintigraphy and combining them with the 3D FEM will lead to new ideas beyond what has been described so far about the mechanism of fracture formation.

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Conflict of Interest

No conflicts of interest between the authors and / or family members of the scientific and medical committee members or members of the potential conflicts of interest, counseling, expertise, working conditions, share holding and similar situations in any firm.

Authorship Contributions

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REFERENCES

1. Krause W. Handbuch der Menschlichen Anatomie. 3rd ed. Hannover: Hahn'sehe Buchhandlung; 1879. [Link]
2. Hwang K, Kim JH, Baik SH. Thickness map of parietal bone in Korean adults. J Craniofac Surg. 1997;8(3):208-12. [Crossref] [Pubmed]
3. Tellioğlu AT, Yilmaz S, Baydar S, Tekdemir I, Elhan AH. Computed tomographic evaluation before cranial bone harvesting to avoid unexpected hazards during aesthetic procedures. Aesthetic Plast Surg. 2001;25(3):198-201. [Crossref] [Pubmed]
4. Jung YS, Kim HJ, Choi SW, Kang JW, Cha IH. Regional thickness of parietal bone in Korean adults. Int J Oral Maxillofac Surg. 2003;32(6): 638-41. [Crossref] [Pubmed]
5. Pensler J, McCarthy JG. The calvarial donor si te: an anatomic study in cadavers. Plast Recon str Surg. 1985;75(5):648-51. [Crossref] [Pubmed]
6. Stölzel K, Bauknecht C, Wernecke K, Schrom T. Sonographische bestimmung der kalottendicke [Measurement of skull thickness by ultrasound]. Laryngorhinootologie. 2007;86(2): 107-11. [Crossref] [Pubmed]
7. Federspil PA, Tretbar SH, Böhlen FH, Rohde S, Glaser S, Plinkert PK. Measurement of skull bone thickness for bone-anchored hearing aids: an experimental study comparing both a novel ultrasound system (SonoPointer) and computed tomographic scanning to mechanical measurements. Otol Neurotol. 2010; 31(3):440-6. [Crossref] [Pubmed]

8. Noakovic D, Meller CJ, Makeham JM, Brazier DH, Forer M, Patel NP. Computed tomographic analysis of outer calvarial thickness for osseointegrated bone-anchored hearing system insertion. Otol Neurotol. 2011;32(3):448-52. [Crossref] [Pubmed]
9. Arntsen T, Kjaer I, Sonnesen L. Skull thickness in patients with skeletal Class II and Class III malocclusions. Orthod Craniofac Res. 2008;11(4):229-34. [Crossref] [Pubmed]
10. Jacobsen PE, Kjaer I, Sonnesen L. Skull thickness in patients with skeletal deep bite. Orthod Craniofac Res. 2008;11(2):119-23. [Crossref] [Pubmed]
11. Nelson RF, Hansen KR, Gantz BJ, Hansen MR. Calvarium thinning in patients with spontaneous cerebrospinal fluid leak. Otol Neurotol. 2015;36(3):481-5. [Crossref] [Pubmed]
12. Chauveau N, Franceries X, Doyon B, Rigaud B, Morucci JP, Celsis P. Effects of skull thickness, anisotropy, and inhomogeneity on forward EEG/ERP computations using a sphe rical three-dimensional resistor mesh model. Hum Brain Mapp. 2004;21(2):86-97. [Crossref] [Pubmed] [PMC]
13. Hagemann D, Hewig J, Walter C, Naumann E. Skull thickness and magnitude of EEG alpha activity. Clin Neurophysiol. 2008;119(6):1271-80. [Crossref] [Pubmed]
14. Reimann F, Talasli U, Gökmen E. Zur röntgenologischen bestimmung der dicke der schädeiknochen und ihrer verbreiterung bei patienten mit schwerer bluterkrankung und hyperplasie des roten knochenmarks [For radiographic determination of the thickness of the skull bones and their widening in patients with severe blood disease and hyperplasia of the red bone marrow]. Fortschr Röntgenstr. 1976;125(6):540-5. [Crossref] [Pubmed]
15. Kattan KR. Calvarial thickening after Dilantin medication. Am J Roentgenol Radium Ther Nucl Med. 1970;110(1):102-5. [Crossref] [Pubmed]
16. Todd TW. Thickness of the male white cranium. The Anatomical Record. 1924;27(5):245-56. [Crossref]
17. Roche AF. Increase in cranial thickness during growth. Hum Biol. 1953;25(2):81-92. [Pubmed]
18. Hansman CF. Growth of interorbital distance and skull thickness as observed in roentgenographic measurements. Radiology. 1966;86(1):87-96. [Crossref] [Pubmed]
19. Adeloye A, Kattan KR, Silverman FN. Thickness of the normal skull in the American Blacks and Whites. Am J Phys Anthropol. 1975;43(1):23-30. [Crossref] [Pubmed]
20. Moreira-Gonzalez A, Papay FE, Zins JE. Calvarial thickness and its relation to cranial bone harvest. Plast Reconstr Surg. 2006;117(6):1964-71. [Crossref] [Pubmed]
21. Hatipoglu HG, Ozcan HN, Hatipoglu US, Yuksel E. Age, sex and body mass index in relation to calvarial diploe thickness and craniometric data on MRI. Forensic Sci Int. 2008;182(1-3):46-51. [Crossref] [Pubmed]
22. Smith K, Politte D, Reiker G, Nolan TS, Hildebolt C, Mattson C, et al. Automated measurement of pediatric cranial bone thickness and density from clinical computed tomography. Annu Int Conf IEEE Eng Med Biol Soc. 2012;2012:4462-5. [Crossref] [Pubmed] [PMC]
23. Baral P, Koirala S, Gupta MK. Calvarial thickness of Nepalese skulls-Computerised Tomographic (CT) study. Anat Physiol. 2014;4(2):1000140. [Link]
24. Lillie EM, Urban JE, Lynch SK, Weaver AA, Stitzel JD. Evaluation of skull cortical thickness changes with age and sex from computed tomography scans. J Bone Miner Res. 2016;31(2):299-307. [Crossref] [Pubmed]
25. Thulung S, Ranabhat K, Bishokarma S, Gongal DN. Morphometric measurement of cranial vault thickness: a tertiary hospital based study. JNMA J Nepal Med Assoc. 2019;57(215):29-32. [Crossref] [Pubmed]
26. Domenech-Fernandez P, Yamane J, Domenech J, Barrios C, Soldado-Carrera F, Knorr J, et al. Analysis of skull bone thickness during growth: an anatomical guide for safe pin placement in halo fixation. Eur Spine J. 2021;30(2):410-5. [Crossref] [Pubmed]
27. Ross MD, Lee KA, Castle WM. Skull thickness of Black and White races. S Afr Med J. 1976;50(16):635-8. [Pubmed]
28. Brown T, Pinkerton SK, Lambert W. Thickness of the cranial vault in Australian Aboriginals. Archaeology & Physical Anthropology in Oceania. 1979;14(1):54-71. [Link]
29. Durbar US. Racial variations in different skulls. J Pharm Sci & Res. 2014;6(11):370-2. [Link]
30. Ross AH, Jantz RL, McCormick WF. Cranial thickness in American females and males. J Forensic Sci. 1998;43(2):267-72. [Crossref] [Pubmed]
31. Smith DR, Limbird KG, Hoffman JM. Identification of human skeletal remains by comparison of bony details of the cranium using computerized tomographic (CT) scans. J Forensic Sci. 2002;47(5):937-9. [Crossref] [Pubmed]
32. Li H, Ruan J, Xie Z, Wang H, Liu W. Investigation of the critical geometric characteristics of living human skulls utilising medical image analysis techniques. Int J Vehicle Safety. 2007;4(2):345-67. [Crossref]
33. Sidler M, Jackowski C, Dirnhofer R, Vock P, Thali M. Use of multislice computed tomography in disaster victim identification--advantages and limitations. Forensic Sci Int. 2007;169(2-3):118-28. [Crossref] [Pubmed]
34. Mahinda HAM, Murthy OP. Variability in thickness of human skull bones and sternum- an autopsy experience. Journal of Forensic Medicine & Toxicology. 2009;26(2):26-31. [Link]
35. Farzana F, Shah BA, Shahdad S, Zia ul Haq P, Sarmast A, Ali Z. Computed tomographic scanning measurement of skull bone thickness: a single center study. Int J Res Med Sci. 2018;6(3):913-6. [Crossref]
36. Dougherty G, Newman D. Measurement of thickness and density of thin structures by computed tomography: a simulation study. Med Phys. 1999;26(7):1341-8. [Crossref] [Pubmed]
37. Ruan J, Prasad P. The effects of skull thickness variations on human head dynamic impact responses. Stapp Car Crash J. 2001;45:395-414. [Crossref] [Pubmed]
38. Delye H, Verschueren P, Depreitere B, Verpoest I, Berckmans D, Vander Sloten J, et al. Biomechanics of frontal skull fracture. J Neurotrauma. 2007;24(10):1576-86. [Crossref] [Pubmed]
39. Got C, Guillon F, Patel A, Mack P, Brun-Cassan F, Fayon A, et al. Morphological and biomechanical study of 146 human skulls used in experimental impacts, in relation with the observed injuries. SAE Transactions. 1983;92(4):528-46. [Crossref]
40. Hodgson VR, Brinn J, Thomas LM, Greenberg SW. Fracture behavior of the skull frontal bone against cylindrical surfaces. SAE Technical Paper. 1970:700909. [Crossref]
41. Deck C, Nicolle S, Willinger R. Human head FE modelling: improvement of skull geometry and brain constitutive laws. IRCOBI Conference-Graz (Austria); 2004. p.7992. [Link]
42. Raul JS, Baumgartner D, Willinger R, Ludes B. Finite element modelling of human head injuries caused by a fall. Int J Legal Med. 2006;120(4):212-8. [Crossref] [Pubmed]
43. Law SK. Thickness and resistivity variations over the upper surface of the human skull. Brain Topogr. 1993;6(2):99-109. [Crossref] [Pubmed]
44. Raul JS, Deck C, Willinger R, Ludes B. Finite-element models of the human head and their applications in forensic practice. Int J Legal Med. 2008;122(5):359-66. [Crossref] [Pubmed]
45. Raymond D, Van Ee C, Crawford G, Bir C. Tolerance of the skull to blunt ballistic temporoparietal impact. J Biomech. 2009;42(15):2479-85. [Crossref] [Pubmed]
46. Hamel A, Llari M, Piercecchi-Marti MD, Adalian P, Leonetti G, Thollon L. Effects of fall conditions and biological variability on the mechanism of skull fractures caused by falls. Int J Legal Med. 2013;127(1):111-8. [Crossref] [Pubmed]

47. Delye H, Clijmans T, Mommaerts MY, Sloten JV, Goffin J. Creating a normative database of age-specific 3D geometrical data, bone density, and bone thickness of the developing skull: a pilot study. J Neurosurg Pediatr. 2015;16(6):687-702. [Crossref] [Pubmed]
48. Foville M. Traité Complet De L'anatomie, De La Physiologie Et De La Pathologie Du Système Nerveux Cérébro-Spinal. 1st ed. Paris: Fortin, Masson Et Cie; 1844. [Link]
49. Baer CEV, Lucae JGC. Zur Morphologie der Rassen-Schädel. Einleitende Bemerkungen Und Beiträge. 1. Auflage. Frankfurt: Druck Und Verlag von Heinrich Ludwig Brönner; 1861. [Link]
50. Broca MP. Sur Le Volume Et La Forme Du Cerveau. Suivant Les Individus Et Suivant Les Races. 1st ed. Paris: Typographie Hennuyer, Rue Du Boulevard; 1861. [Link]
51. Henle J. Handbuch der Systematischen Anatomie des Menschen. 3rd ed. Braunschweig: Druck Und Verlag von Friedrich Vieweg Und Sohn; 1871. [Link]
52. Todd TW. Cranial capacity and linear dimensions, in white and negro. Am J Phys Anthropol. 1923;6(2):97-194. [Crossref]
53. Todd TW. The effect of maceration and drying upon the linear dimensions of the green skull. J Anat. 1923;57(Pt 4):336-56. [Pubmed] [PMC]
54. Anderson RJ. Observations on the thickness of the human skull. The Dublin Journal of Medical Science. 1882;74:270-80. [Crossref]
55. Twiesselmann F. Méthode pour l'évaluation de l'épaisseur des parois crâniennes. Bulletin Du Musée Royal d'Histoire Naturelle de Belgique. 1941; 17(48):1-33. [Link]
56. Ivanhoe F. Direct correlation of human skull vault thickness with geomagnetic intensity in some Northern Hemisphere Populations. Journal of Human Evolution. 1979;8:433-44. [Crossref]
57. Sullivan WG, Smith AA. The split calvarial graft donor site in the elderly: a study in cadavers. Plast Reconstr Surg. 1989;84(1):29-31. [Crossref] [Pubmed]
58. Ishida H, Dodo Y. Cranial thickness of modern and neolithic populations in Japan. Hum Biol. 1990;62(3):389-401. [Pubmed]
59. Broadbent BH. A new x-ray technique and its application to orthodontia. The Angle Orthodontist. 1931;1(2):45-66. [Link]
60. Letts M, Kaylor D, Gouw G. A biomechanical analysis of halo fixation in children. J Bone Joint Surg Br. 1988;70(2):277-9. [Crossref] [Pubmed]
61. Koenig WJ, Donovan JM, Pensler JM. Cranial bone grafting in children. Plast Reconstr Surg. 1995;95(1):1-4. [Crossref] [Pubmed]
62. Newman DL, Dougherty G, al Obaid A, al Hajrasy H. Limitations of clinical CT in assessing cortical thickness and density. Phys Med Biol. 1998;43(3):619-26. [Crossref] [Pubmed]
63. Prevrhal S, Engelke K, Kalender WA. Accuracy limits for the determination of cortical width and density: the influence of object size and CT imaging parameters. Phys Med Biol. 1999;44(3):751-64. [Crossref] [Pubmed]
64. Prevrhal S, Fox JC, Shepherd JA, Genant HK. Accuracy of CT-based thickness measurement of thin structures: modeling of limited spatial resolution in all three dimensions. Med Phys. 2003;30(1):1-8. [Crossref] [Pubmed]
65. Chompoopongkasem K, Chandraphak S, Chiewvit P, Aojanepong C. [Calvarial thickness and its correlation to three-dimensional CT (3D-CT) scan]. Reg 6-7 Med J. 2008;27(4):1171-83. [Link]
66. Tretbar SH, Plinkert PK, Federspil PA. Accuracy of ultrasound measurements for skull bone thickness using coded signals. IEEE Trans Biomed Eng. 2009;56(3):733-40. [Crossref] [Pubmed]
67. Voie A, Dirnbacher M, Fisher D, Hölscher T. Parametric mapping and quantitative analysis of the human calvarium. Comput Med Imaging Graph. 2014;38(8):675-82. [Crossref] [Pubmed]