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TECHNICAL NOTE

ANTHROPOLOGY

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Ossification Degrees of Cranial Sutures Determined with Flat-Panel Computed Tomography: Narrowing the Age Estimate with Extrema

ABSTRACT: Since Broca's time (1824–1880), ossification of the neurocranial sutures has been used as a characteristic of age. Current approaches include the visual macroscopic examination of ecto and endocranial sutures. The evaluation of the cross-section of sutures usually necessitates the destruction of the neurocranium. In a nondestructive alternative approach that was tested within the context of the "Digital Forensic Osteology" project that ran in cooperation with the Virtopsy®-Project, it emerged that the resolution of conventional multi-slice computed tomography data sets was not high enough to image sutures. Thus for the experiments presented here, the eXplore Locus Ultra flat-panel computed tomography scanner from GE Healthcare was used. Calottes were scanned during autopsy and then immediately returned to the corpse. So far, the skullcaps of 221 individuals have been scanned. The cross-sections of 14 suture segments could be assessed for seven previously defined stages of ossification. In a converse step, the 14 highest and lowest age estimate values corresponding to the individual stages of suture closure found were estimated for each calotte. The obtained ranges narrowing down the age estimate were evaluated with statistics. A mean value of 43.31 years for the range of narrowed age estimates shows that this method can be a useful aid in estimating age. The results of intra- and inter-observer tests showed good overall agreement between the findings of three observers. This method is suitable for a nondestructive age estimation and can be used for the entire calotte.

KEYWORDS: forensic science, forensic anthropology, age determination by skeleton, cranial sutures, flat-panel CT

In forensic osteology, age estimation is of immense importance (1,2). The macroscopic assessment of cranial suture ossification has, in this context, largely been described in the literature as an unreliable and highly variable method: The first articles published on this subject date back to the 19th century and are based on the observation that cranial sutures, similar to epiphyseal plates, show ossification that progresses with age (3–8). In later studies, statistic analysis indicated a significant correlation between suture closure and age, but age estimations based solely on the assessment of cranial sutures must be rejected because of the wide confidence intervals found in more recent studies (9–16). Current technological developments in the field of computed tomography (CT) permit the acquisition of high-resolution images of bone structures and, with the added advantage of being nondestructive, allow further information about fine bone structures, such as the ossification status of cranial sutures or the extent of gunshot injuries to the skull, to be won (17,18).

In our work to date, we have attempted to examine the internal suture structure in the classic segments of the sagittal-, coronal-, and lambdoid-sutures (Fig. 1) (11,12) with a flat-panel CT modality to determine a correlation between age and seven stages of suture closure. We could not, however, determine an advantage here over the macroscopic methods that have so far been described (19). The purpose of this study was to examine whether, analogous to the "integrated method" for the estimation of time since death (20), an age estimate based on extrema, that is the minimum and maximum age observed for each of the stages of suture closure for each suture segment, is feasible.

Materials and Methods

A total of 221 calvaria of known sex and age were examined. These were obtained from autopsies performed at the Department of Legal Medicine at the University Hospital of Gießen and Marburg during 2007/2008. The skullcaps came from 148 men, aged between 0.8 and 100.0 years (mean value 48.9, SD = 18.4), and 73 women, aged between 0.3 and 98.0 years (mean value 56.6, SD = 27.0). They were collected continuously during the course of autopsies. Exclusion criteria were diseases that can affect bones (i.e., tumor, M. Paget, tuberculosis), any known deceleration of aging in childhood (i.e., caused by malnutrition), and deformities such as craniostenoses or healed cranial fractures. After opening the cranium in a horizontal cut with an oscillating saw, as is standard procedure in the examination of the brain in any autopsy, the skullcaps were scanned with the flat-panel CT eXplore Locus Ultra system (GE Healthcare, London, ON, Canada) (17,18) and were

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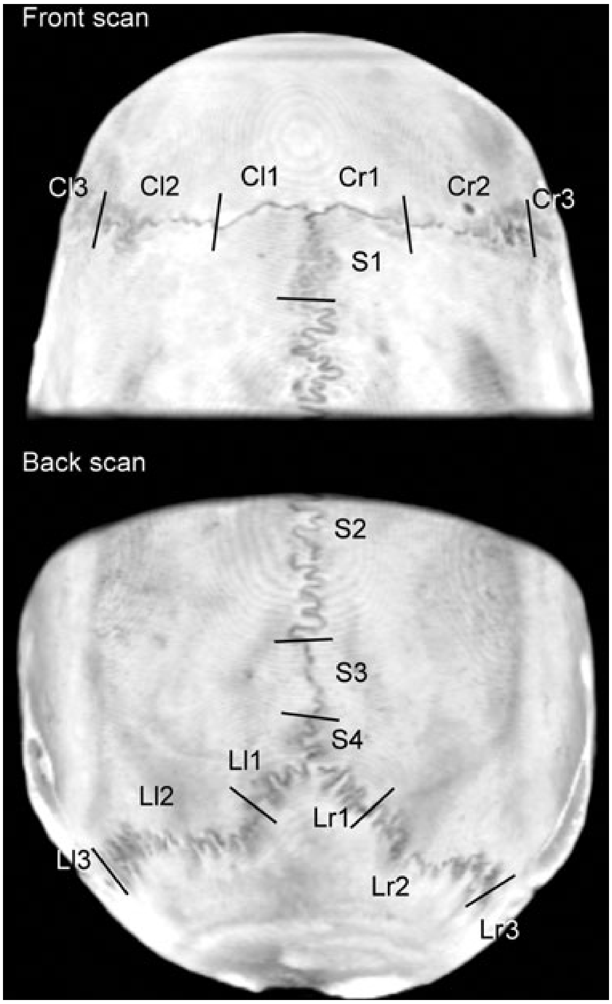

FIG. 1—*Image of the ectocranial suture divisions as seen on a 3D overview when viewing the CT data with the Advantage Workstation, based on the suture division by Oppenheim (11,12). S, sagittal suture; C, coronal suture; L, lambdoid suture; r, right; l, left.*

subsequently returned to the corpse unaltered. For technical reasons (data volume, calculating capacity) in each case, two scans were necessary to capture the entire skullcap.

The data sets were processed with an Advantage Workstation (Version 4.1; GE Medical Systems, Buc, France), a Linux computer with a Dual-Core 2.2 GHz Processor and 4 GB RAM. With the Volume Viewer Voxtool 3.0.58c software (GE Medical System, Buc, France), it was possible to view not only freely rotatable 3D images, but also 2D sectional views.

The evaluation was carried out blind on data sets that retained only their serial autopsy number so that they could later be matched with the data about their actual age and sex. Following the division of the cranial sutures into 16 segments described by Oppenheim (11,12), each segment was examined for its degree of ossification. Frequently, only the four medial segments of the lambdoid suture could be evaluated because of the typical cut used in opening the cranium. This is why only 14 of the described segments were considered in the evaluation. Analogous to the macroscopic evaluation of suture obliteration, and based on Broca's classification of the degree of suture obliteration (cited from 9,11), the ossification of each segment was scored as belonging to one of a total of seven stages (Table 1, Fig. 2). To this end, sectional views of the suture segments in the coronal-, axial-, and sagittal-planes were viewed with the Volume Viewer software, using a window of 1600 and a level of 1000. A 3D overview was used as an orientation guide. An oblique mode, which allows sectional planes to be freely rotated, was not used to keep the evaluation as standardized and examiner independent as possible. Virtual

TABLE 1—*Description of the seven stages of suture closure for the evaluation with flat-panel CT.*

Stage		Percentage of Ossification (%)
0	Totally open	0
1	Open, beginning closure	<10
2	Moderate closure	10–33
3	Evident closure	34–66
4	Considerable closure	67–90
5	Closed, relics of the ossification process visible	>90
6	Total closure	100

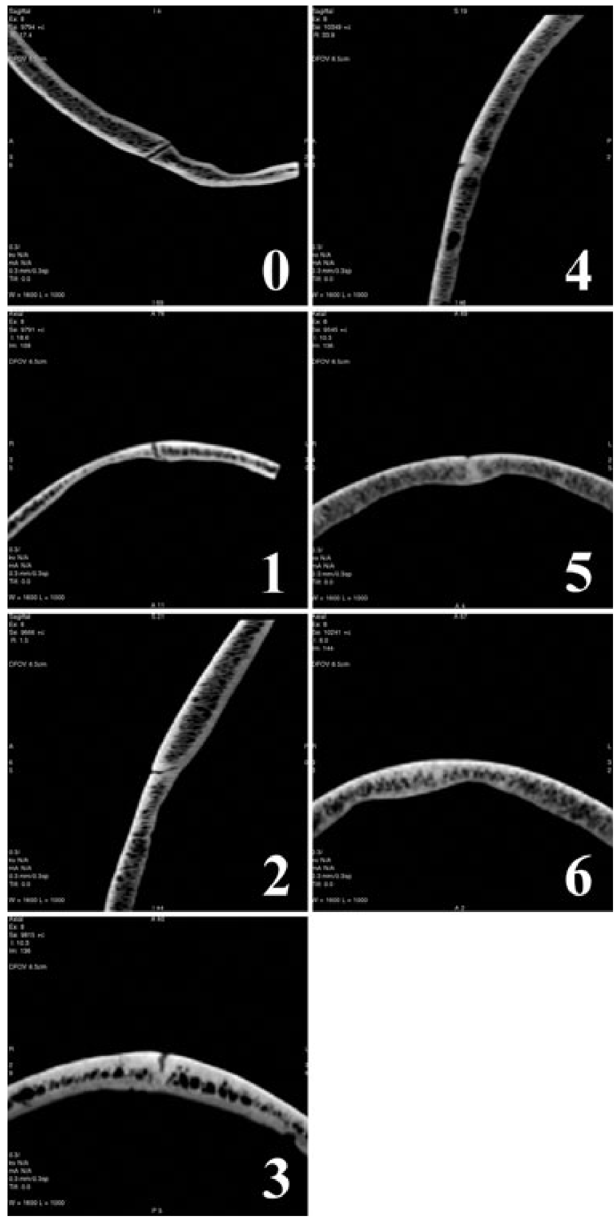

FIG. 2—*Image of the seven stages of ossification as seen when viewing the CT data with the Advantage Workstation (compare Table 1).*

measurements of the open or, respectively, closed parts of the suture could be taken to facilitate a more exact assignment to one of the stages.

The data were statistically analyzed with the SPSS 16.0 software, from SPSS Inc. (Chicago, IL). The evaluation and organization of the data was performed with Microsoft Access 9.0 and Excel 9.0. The influence of sex on the closure of cranial sutures was tested using Mann–Whitney and Wilcoxon tests. As we could not find a significant difference between men and women in regard to the dependence of age on the degree of ossification, both sexes were evaluated together (19). More than half a year after completion of the evaluation, intra- and inter-observer tests were performed. To this end, 20 calvaria, drawn at random from within the samples, were assessed by the original observer and two additional independent observers in a blind examination. Weighted kappa coefficients (κ_w) (21) were calculated for the intra-observer test. Inter-observer agreement was evaluated using Light's kappa coefficient (22) with squared weights. The weighted kappa coefficient is a useful measure of agreement for ordered data as disagreements of varying gravity contribute to its value. General guidelines for the interpretation of kappa suggest that values between 0.81 and 1.00 should represent "almost perfect" agreement, 0.61–0.80 "substantial" agreement, 0.41–0.60 "moderate" agreement, 0.21–0.40 "fair" agreement, and 0.00–0.20 "slight" agreement (23). Kappa coefficients were computed using the psy 0.7 package in R version 2.8.1 (The R Foundation for Statistical Computing, Vienna, Austria).

Results

A Levene test, which was used to test the influence of sex on the ossification of cranial sutures, revealed that the variances in the mean suture stages were inhomogeneous ($p < 0.05$) for the male versus the female group. After a Welchtest, the null hypothesis was retained (no significant difference in the mean values of the mean suture stages for both groups). We then used Mann–Whitney and Wilcoxon statistics to test the null hypothesis that the two samples, "mean suture closure stages of males" and "mean suture closure stages of females," come from the same population. This had to be accepted ($p = 0.105$). The influence of sex on the closure of cranial sutures can therefore not be verified (19).

The first evaluative step was to draw up a table for the minimum and maximum age observed for each of the seven stages of suture closure and for each of the 14 suture sections in the sample, so that 7*14 = 98 age ranges were available to narrow the age estimate (Table 2). The youngest, and at the same time only, individual who was found to have stage 6 in all segments was a 42.7-year-old man. Stage 0 in all segments was found only for five female infants and for a 38.2-year-old woman.

In a following, converse step, for each calotte, the 14 highest and lowest age estimate values corresponding to the individual stages of suture closure found for each calotte were read from the table. Similar to the "integrated method," the age span was narrowed for each calotte and the range was noted. In Table 3, an example case illustrating the method can be found. The key statistical values for the distribution of the range of age limits are given in Table 4. Kappa statistics for the intra- and inter-observer tests can be found in Table 5.

Discussion

Current investigations are looking into different methods for determining age in a forensic setting, and radiological methods are increasingly becoming popular (24–29). To the best of our

TABLE 2—*Age intervals obtained from the minimum and maximum ages observed for each suture section and stage of suture closure.*

		Age	
Section	Stage	Minimum	Maximum
S1	0	0.26	46.66
	1	17.97	66.80
	2	22.36	99.99
	3	27.36	91.26
	4	25.71	94.54
	5	26.72	98.00
	6	41.81	93.95
S2	0	0.26	64.34
	1	17.97	49.16
	2	25.24	99.99
	3	22.36	91.26
	4	25.71	94.54
	5	30.72	98.00
	6	42.67	88.19
S3	0	0.26	60.96
	1	17.97	61.43
	2	22.36	67.11
	3	27.36	99.99
	4	26.72	88.19
	5	25.71	93.95
	6	41.25	98.00
S4	0	0.26	64.34
	1	8.30	61.43
	2	17.97	99.99
	3	26.72	94.54
	4	27.56	88.19
	5	25.71	93.95
	6	41.25	98.00
Cl1	0	0.26	52.49
	1	2.98	61.45
	2	6.53	66.80
	3	26.72	99.99
	4	33.60	94.54
	5	25.71	98.00
	6	42.67	84.98
Cl2	0	0.26	61.45
	1	0.78	52.49
	2	25.88	55.10
	3	12.30	91.26
	4	25.71	99.99
	5	39.04	94.54
	6	42.67	93.95
Cl3	0	0.26	52.49
	1	1.19	61.45
	2	12.30	81.29
	3	0.78	84.19
	4	22.36	99.99
	5	33.60	98.00
	6	42.67	93.95
Cr1	0	0.26	52.49
	1	26.08	61.45
	2	22.36	82.92
	3	26.72	99.99
	4	25.71	94.54
	5	39.04	98.00
	6	42.67	83.14
Cr2	0	0.26	52.49
	1	1.19	46.66
	2	18.08	73.72
	3	12.30	91.26
	4	25.71	99.99
	5	39.04	98.00
	6	42.67	93.95
Cr3	0	0.26	46.66
	1	0.78	52.49
	2	18.08	68.48
	3	12.30	98.00
	4	27.36	99.99
	5	25.71	87.87
	6	42.67	93.95

TABLE 2—(*Continued*)

Section	Stage	Age Minimum	Age Maximum
Ll1	0	0.26	80.83
	1	12.30	81.29
	2	18.08	99.99
	3	22.36	94.54
	4	25.71	88.19
	5	41.81	87.87
	6	42.67	98.00
Ll2	0	0.26	80.83
	1	6.53	81.29
	2	18.08	89.54
	3	27.36	99.99
	4	26.08	88.19
	5	25.71	93.95
	6	42.67	98.00
Lr1	0	0.26	80.83
	1	25.73	61.43
	2	12.30	89.54
	3	27.39	99.99
	4	26.08	88.72
	5	25.71	93.95
	6	42.67	98.00
Lr2	0	0.26	80.83
	1	12.30	53.99
	2	18.08	99.99
	3	26.72	94.54
	4	25.71	88.19
	5	41.25	93.95
	6	42.67	98.00

TABLE 3—*Example for the narrowing of an age estimate with extrema as listed in Table 2.*

Section	Stage	Age Minimum	Age Maximum
S1	1	17.97	66.80
S2	1	17.97	**49.16**
S3	1	17.97	61.43
S4	1	8.30	61.43
Cl1	2	6.53	66.80
Cl2	3	12.30	91.26
Cl3	3	0.78	84.19
Cr1	1	**26.08**	61.45
Cr2	3	12.30	91.26
Cr3	3	12.30	98.00
Ll1	2	18.08	99.99
Ll2	2	18.08	89.54
Lr1	2	12.30	89.54
Lr2	2	18.08	99.99
Age estimate		**26.08**	**49.16**

Numbers in bold indicate the values which led to the extrema of the estimated age.

TABLE 4—*Descriptive statistics for the range of narrowed age estimates.*

	Statistic	Standard Error
Mean	43.32	0.81508
95% Confidence interval for mean		
Lower bound	41.71	
Upper bound	44.92	
Median	45.21	
Variance	146.82	
Standard deviation	12.12	
Minimum	18.78	
Maximum	72.60	
Range	53.82	
Interquartile range	16.02	

TABLE 5—*Weighted kappa (κ_w) statistics from the intra- and inter-observer test.*

	Inter-observer			Intra-observer		
	κ_w			κ_w		
Segment		95% CI			95% CI	
S1	0.889	0.80	0.94	0.934	0.89	0.98
S2	0.871	0.77	0.93	0.933	0.79	0.99
S3	0.851	0.74	0.92	0.980	0.92	1.00
S4	0.915	0.87	0.95	0.974	0.94	0.99
Cl1	0.665	0.49	0.84	0.854	0.63	0.97
Cl2	0.759	0.58	0.86	0.848	0.71	0.94
Cl3	0.493	0.28	0.69	0.770	0.43	0.94
Cr1	0.685	0.51	0.82	0.935	0.81	1.00
Cr2	0.679	0.37	0.84	0.889	0.74	0.97
Cr3	0.522	0.25	0.74	0.726	0.38	0.90
Ll1	0.736	0.56	0.87	0.876	0.73	0.96
Ll2	0.754	0.62	0.86	0.939	0.85	0.99
Lr1	0.740	0.47	0.87	0.821	0.69	0.93
Lr2	0.681	0.51	0.83	0.902	0.77	0.96

knowledge, this study is the first to investigate the question of whether it is possible to estimate age by assessing the ossification degree of the cranial sutures with the aid of flat-panel CT.

A mean value of 43.31 years for the range of narrowed age estimates shows that this method can be a useful aid in estimating age. Table 3 contains a selected case with considerable results. With aid of the extrema, as listed in Table 2, the age could be narrowed to 26.08–49.16 years. In individual cases, it is possible to narrow down the age to *c.* ±10 years. A comparison with our previous results and the literature reveals that this method is, at least for the current sample size, superior to an age estimate based on a linear regression model. Here we found a 95% confidence interval of ±31.1 years for the age estimate (19). Comparable ranges can be found in the studies by Perizonius (12) and Meindl and Lovejoy (13). Dorandeu et al. (16) found a prediction range of 18.07–69.62 years for their age prediction formula. Schmitt and Tamáska (11) found a 95% confidence interval of ±32 years for the outer sutures, and of ±25 years for the inner sutures, in their macroscopic assessment of cranial sutures.

The weighted kappa values from the intra- and inter-observer tests indicate a considerable overall agreement not only between the first and second examination through the first observer but also between the results obtained by all three observers. Slight differences can be seen for the individual segments, with worst results for the segments Cl3 and Cr3, and best results for the segments of the sagittal suture. An explanation could be that the outer segments of the coronal suture are shorter than those of the sagittal suture and it is therefore harder to assess the demarcation between neighboring segments here during examination. Also, as a result of the thinner skull found in the temporal area, it is harder to classify the degree of ossification to a certain stage of suture closure here.

Conclusion

Our results show that an age estimate based on the cross-sectional ossification degree of cranial sutures, determined with flat-panel CT, can be narrowed down with the aid of extrema and is feasible in practice. In respect to the narrowing down of the age estimate, this method shows clear advantages over other present methods based on the assessment of suture ossification. The application of this method could be particularly valuable in conjunction with other methods and should be confirmed by a greater number of cases. Further research, including the development of tailor-made software for a verifiable, automated evaluation of CT data sets, is being conducted.

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