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Estimating adult age: cranial suture closure

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Abstract

Since immemorial time the cranial sutures have attracted the attention of any one who learns on a skull, as they are surprising. We give a glance of history about several anthropologists who studied these sutures, and explain the interest of this approach. We try to explain the actual value of the ectocranial, palatine and other craniofacial sutures. Their role in estimating age at death is integrated among other observations, such as odontological expertise or the study of bones belonging to the postcranial skeleton e.g. hip bone (pubic symphysis, auricular surface) and the sternal extremity of the 4th rib. We also describe the limits and the imprecision of our study, and include the present and the future in the forensic approach of cranial sutures.

***Keywords*:** physical anthropology; forensic anthropology; forensic science; cranial sutures; palatine sutures; facial sutures; age at death.

Résumé

Les sutures crâniennes ont depuis des temps immémoriaux, attiré l'attention de tout qui se penche sur un crâne, tant elles sont surprenantes. Nous proposons tout d'abord un aperçu historique des divers anthropologues qui ont étudié ces sutures et en donnons l'intérêt de cette approche. Nous décrivons également l'intérêt réel des sutures ectocrâniennes, palatines et autres sutures crânio-faciales. Leur place dans l'estimation de l'âge au décès est à intégrer parmi les autres observations essentielles telles que l'expertise odontologique et l'étude des os appartenant au squelette postcrânien, comme l'os coxal (symphyse pubienne, surface auriculaire) et l'extrémité sternale de la 4ème côte. Nous décrivons également les limites, l'imprécision de notre étude, et incluons le présent et l'avenir dans l'approche médico-légale de ces sutures crâniennes.

Mots-clés : anthropologie physique ; anthropologie forensique ; science forensique ; sutures crâniennes ; sutures palatines ; sutures faciales ; âge au décès.

1. INTRODUCTION

Since immemorial time the cranial sutures have attracted the attention of any one who learns on a skull, as they are surprising.

Just observe the spectacular indented boundaries that formed by the vault sutures, interpenetrations they create, to ask a multitude of questions about their formation, development and progressive fusion.

Yet when the disease appears (e.g. in the case of craniosynostosis), we can imagine the fundamental role played by these vault sutures in the development of the skull and its brain precious content.

And one can only marvel at how these interdigitations evolve, physical phenomenon looking like the sheets of ice floe interpenetrating, but especially biological phenomenon depending on factors such products by the underlying dura (OPPERMAN *et al.*, 1993; OPPERMAN *et al.*, 2000; OPPERMAN *et al.*, 2002; RAWLINS & OPPERMAN, 2008; SHIBAZAKI-YOROZUYA *et al.*, 2012; LIU *et al.*, 2013).

This proximity may explain why the endocranial sutures in front of intracranial diploe, are obliterated faster than the ectocranial ones.

After this introduction, a glance to history is not without interest, since already Leonardo da Vinci was interested in the cranial sutures and

then obviously our compatriot Andre Vesalius, who established a relationship between age and synostosis of cranial sutures.

He associates them also with "union and welding vertebrae that is also observed in old age" (VÉSALE, 1543).

Many researchers, anthropologists and anatomists have continued this approach.

We can mention the spheno-occipital synchondrosis study by Welcker (1866), the proposal of a coefficient of obliteration in five stages by Ribbe (1885), the approach of age with sutures proposed by Dwight (1890), the important work of Ferraz de Macedo on a very large sample of skulls (1892), the influence of sexual dimorphism and the degree of synostosis in endocranial and ectocranial sides of the diploe by Frederic (1906), the work of the latter served the development of the famous anthropological Martin's textbook (1914, 1928).

Thereafter, Todd and Lyon (1924, 1925) studied the rate of sutural obliteration, but with a ± 15-year estimation error, which was confirmed by Masset (1971), Nemeskéri (1960) and Perizonius (1984).

Returning to Masset, this resulted in a mathematical and statistical approach, also confirming the influence of gender in the evolution of sutural obliteration (1982, 1989; MASSET *et al.*, 1989).

Indeed, for the same age, brachycephalic skulls are significantly slightly less synostosed than dolichocephalic skulls.

Other sutures also interested anthropologists such as Meindl and Lovejoy (1985) who studied the lateral vault sutures, or Mann (1987, MANN *et al.*,1987, 1991) whose work was oriented towards the palatine sutures, and revised by other anthropologists later, with results sometimes good and sometimes more mixed (GINTER, 2003, 2005; GRUSPIER & MULLEN, 1991).

In 2020, must we still believe in the value of these sutures?

Our response will be nuanced, after having extensively studied not only classic vault sutures but also the pterion area, the palatine sutures and other facial sutures, among various and elderly populations.

It is also a response not only made after work in laboratory but also and above all an answer from a practitioner's field of anthropological and forensic expertise.

Generally, these sutures are discredited, since they do not provide the desired accuracy, facing other techniques such as odontology, study of the pubic symphysis, sternal end of the fourth rib, and auricular surface of the coxal bone.

Nevertheless our anthropological experience tells us that the skull is often the only piece of bone assigned for expertise.

We must therefore try to extract maximum information, especially in a forensic context.

Remember also the interesting role of sutures in specimens with impaired growth and / or intentional cranial deformation (O'BRIEN & SENSOR, 2008), but the significance of the differential diagnosis between suture and cranial fracture as well (THARP & JASON, 2009).

Furthermore, the cranial sutures can lead - as frontal sinuses - to useful comparative elements of identification in forensic anthropology (provided you have *ante mortem* X-rays of CT-Scan).

Consequently, there can be no question to disregard these interesting aspects of the cranial anatomy, although significant question marks remain as present.

2. MATERIAL AND METHOD

2.1. Osteological material

We shall not describe into detail the osteological collections we studied. All information about these collections is available through our publications about this subject (BEAUTHIER

et al., 2008a, 2008b, 2010; LEFÈVRE *et al.*, 2005; BEAUTHIER, 2009), including the "Bone Nice Collection" from the forensic anthropology laboratory of Nice University (France; Prof. G. Quatrehomme), the "Schoten Collection" and the "Châtelet Collection" (Royal Institute of Natural Sciences, Belgium; ORBAN & VANDOORNE, 2006; ORBAN *et al.*, 2002; POLET *et al.*, accepted for publication).

Many skulls (a collection of a thousand skeletons from the Dunes' Abbey in Koksijde - Royal Institute of Natural Sciences of Belgium; TWIESSELMANN & BRABANT, 1967; ORBAN *et al.*, 1989, 2002; WERQUIN & POLET, 2005; ORBAN & VANDOORNE, 2006; WERQUIN *et al.*, 2007) were then studied by our team for several years, with a triple approach to estimating age at death: i) sutural study; ii) dental study and iii) study of postcranial skeleton (pubic symphysis and sternal end of the fourth rib).

2.2. Investigating methods

2.2.1. Age classes

Rather than try to approach as closely as possible the age (we have set in this regression equations and refer the interested reader to our publications), we considered more accessible and practical to limit this approach to age groups (Tab. 1), adapting those used by Acsádi and Nemeskéri (1970), by the fact that our samples provided access to very elderly adults, leaving the usually encountered in the literature studies (Range of our study: i) females are 19-101 y; ii) males 19-96 y).

Age classes	*Age Range (years)*	*Age Group*
I	≤ 20	Infant and juvenile
II	21–39	Young Adult
III	40–59	Mature Adult
IV	60–79	Old Adult
V	≥ 80	Very old Adult

Tab. 1 - Five age classes.

2.2.2. Sutural study

We explored all the sutures presented in Table 2.

2.2.2.1. Ectocranial vault sutures

We use the Acsádi et Nemeskéri method (1970) i.e. divisions suture into subparts and estimation of scale 0-4 (Tab. 2, Tab. 3 and Fig. 1).

2.2.2.2. Lateral vault sutures

We quickly left this method, considering its limited use, since it provides no benefit *vs* conventional vault sutures (LEFÈVRE *et al.*, 2005).

Ectocranial sutures (ec)	*Sutura coronalis*	3 subparts x 2 (R & L)	16 segments
	Sutura sagittalis	4 subparts	
	Sutura lambdoidea	3 subparts x 2 (R & L)	
Palatine sutures (p)	*Sutura incisiva* (IN)	2 subparts x 2 (R & L)	15 segments
	Sutura palatina mediana		
	(AMP)	*Pars anterior*: 3 subparts	
	(PMP)	*Pars posterior*: 2 subparts	
	Sutura palatina tranversa (TP)	3 subparts x 2 (R & L)	
Other facial sutures (fz)	*Sutura internasalis*		
	Sutura intermaxillaris		
	Sutura nasomaxillaris		
	Sutura frontonasalis		
	Sutura frontomaxillaris		
	Sutura zygomaticomaxillaris		
	Sutura fronto-zygomatica		
	Sutura temporo-zygomatica		

Tab. 2 - Sutural study.

International terminology	*Subparts*	
Sutura coronalis	Between frontal bone and parietal bones	
	C1	*Sutura coronalis, pars bregmatica*
	C2	*Sutura coronalis, pars complicata*
	C3	*Sutura coronalis, pars stephanica & pars pterica (C4)*
Sutura sagittalis	On median sagittal line, between the two parietal bones	
	S1	*Sutura sagittalis, pars bregmatica*
	S2	*Sutura sagittalis, pars verticis*
	S3	*Sutura sagittalis, pars obelica*
	S4	*Sutura sagittalis, pars lambdatica*
Sutura lambdoidea	Between occipital bone and parietal bones	
	L1	*Sutura lambdoidea, pars lambdatica*
	L2	*Sutura lambdoidea, pars intermedia*
	L3	*Sutura lambdoidea, pars asterica*

Tab. 3 - Vault sutures (the abbreviations are the same used on Figure 1).

2.2.2.3. Palatine sutures

Palatine sutures were divided into subparts (see Tab. 2 and Fig. 2) and sutural fusion of each of these subparts was rated on a scale of 0-4 in order to obtain a coefficient (C_p) of sutural fusion.

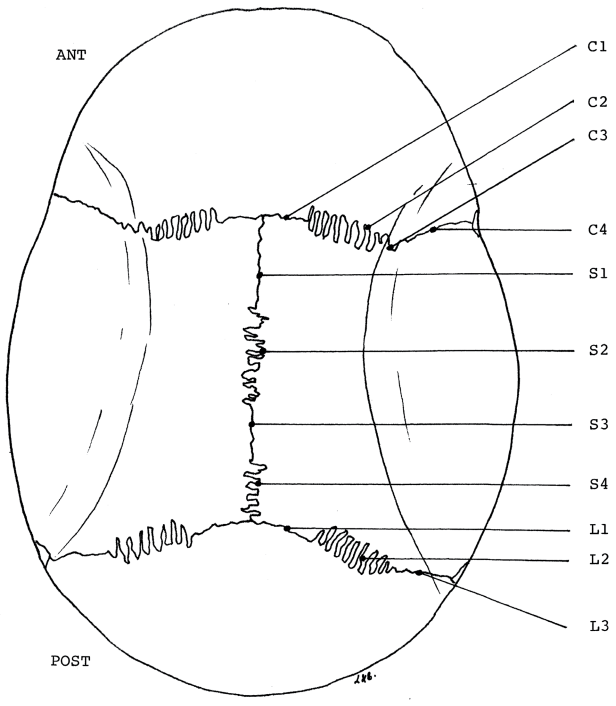


Fig. 1 - *Norma verticalis*. Ectocranial vault sutures and their subparts. Drawing: © J.-P. Beauthier.

2.2.2.4 Other facial sutures

It was the same with other facial sutures, we studied more globally because their small size.

2.2.3. Sutural evolution

We estimated the sutural evolution as shown in Figure 3, inspired by the descriptive and score method of Acsádi and Nemeskéri (1970; KROGMAN & İŞCAN, 1986), as well as those based on evolution in percentage of fusion following Masset (1971, 1982, 1989; MASSET *et al.*, 1989) and Mann (1987, MANN *et al.*, 1987, 1991).

Both evaluations are substantially identical and practices.

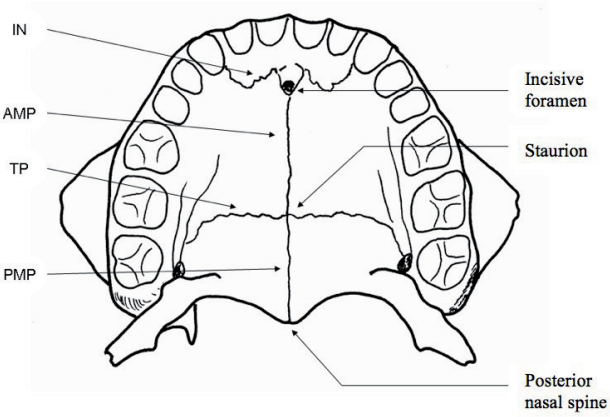


Fig. 2 - Hard palate (inferior view). Drawing: © J.-P. Beauthier.

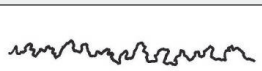
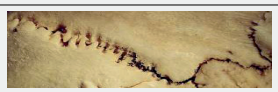
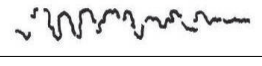
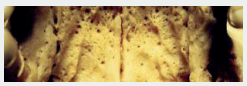
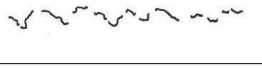
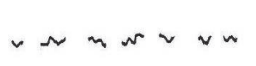
Sutural fusion (scale 0-4)				*Sutural description*	*% closure =*
	Schema from Krogman and İşcan (1986)	Cranial vault	Palate		
0				Open diastatic suture There remains a small space between the bone edges	0 %
1				Closed suture but clearly visible as a continuous line, often as a zigzag	≤ 25 %
2				The sutural line becomes thinner with less zigzag and sometimes interrupted by a complete obliteration area	± 50 %
3				Only a few lines still indicate the site of the suture	± 75 %
4				Suture completely disappeared. Its location is no longer recognized	100 %

Fig. 3 - Sutural evolution. Pictures: © J.-P. Beauthier.

On the assessment based on the 0-4 scale, each subpart is thus noted. The coefficient of ectocranial fusion (C_{ec}) is calculated by dividing the total sum by 16. The coefficient of palatine suture fusion (C_p) is calculated by dividing the total by 15. Thus C_{ec} and C_p result in a range 0-4. These coefficients are linked to the five age classes described in Table 1.

We also estimate but more generally, the fusion of the different other facial sutures (nasal, maxillary, zygomatic sutures; Tab. 2).

3. RESULTS

Rather than the scales 0-4 and the statistical approaches (intra-observer; interobserver; ANOVA reliability tests; Cohen's Kappa test of reliability), we propose a useful table, with the mean coefficients interesting all the sutures we have studied, under a percentage (Tab. 4).

All details are available on our online (free access) publication (Beauthier, 2009).

Classes	*Mean ectocranial coefficient (C_{ec}) (%)*	*Mean palatine coefficient (C_p) (%)*	*Mean fronto-naso-maxillo- zygomatic coefficient (C_{fz}) (%)*
I	11	54.2	8.33
II	28.3	61.11	9.72
III	60.3	72.46	34.72
IV	68.5	83.38	48.76
V	73.5	85.42	51.76

Tab. 4 - Sutural obliteration (%) in the five age classes (combined genders). The mean coefficients are easily obtained, transforming the values 0-4 in % - with value 4 = 100 %)

We also compare the first stage of fusion with these described in the literature for i) cranial sutures [(COHEN, 1997) from (TODD & LYON, 1924, 1925; CAFFEY, 1961; MIROUE & ROSENBERG, 1975; KOKICH, 1976; COHEN, 1993)] [(Tab. 5) and ii] palatine sutures [(MANN *et al.*, 1991) Tab. 6].

4. DISCUSSION

Thus we can draw useful information below:

a. We found a match between both approaches (82 % agreement).
b. Our results interesting **cranial sutures** join those of Acsádi and Nemeskéri, and also Masset.
c. We have not performed an approach of endocranial sutures because a cranial section was impossible.
d. We observed successive sequences of sutural obliteration namely: **sagittal → lambdoid → coronal** in male individuals, as described in the literature. By cons, in females, the sequence is as follow: **sagittal → coronal → lambdoid.**
e. Our study confirms the fact that the progression of palatine suture obliteration is globally the same than the progression of vault suture obliteration. Nevertheless, the other facial sutures (nasal, maxillary, zygomatic sutures) fuse later (QUATREHOMME *et al.*, 2015). The work of Wang in *Macaca mulatta* result in the following sequence: ***neurocranium → basicranium → palate → face*** (WANG *et al.*, 2006a, 2006b).

Cranial sutures	*Beginning of closing process (years)*	*In our series*
Metopic	2	-
Sagittal	22	65
Coronal	24	29
Lambdoid	26	29
Facial sutures		
Palatines (without incisive suture)	30-35	
Fronto-maxillary	68-71	19
Fronto-zygomatic	72	44
Zygomatico-temporal	70-71	42.5
Zygomatico-maxillary	70-72	29
Fronto-nasal	68	42.5
Naso-maxillary	68	27.5
Internasal	-	39
Intermaxillary	-	39

Tab. 5 - Cranial sutures. Age of beginning of closing.

Palatine sutures	*Beginning of closing process (years)*	*In our series*
Incisive	16	(*)
Transverse	22	19
Median palatine (posterior part)	25	19
Median palatine (anterior part)	27	33

(*) One intermediate stage at 19 years and one case of total fusion at also 19 years. Our sampling was more oriented to old and very old individuals.

Tab. 6 Palatine sutures. Age of beginning of closing.

f. We note that there are very few subjects with complete ectocranial obliteration, even at a very old age (MANN, 1987; SCHUMACHER, 1968, 1973). In such cases, facial obliteration is still incomplete.

g. Metopic suture remains a peculiarity: it closes in principle at two years old, but sometimes it persists either as a vestigial suture in the glabellar region, either as a real metopic suture (in about 4 % of individuals in our study).

h. If there are individuals with complete palatine fusion, the closure of the other facial sutures remains incomplete (about 65 %).

i. We also note that the average closure is less pronounced in women than in men.

j. About **palatine sutures**, we also observe the same progression than that described by Mann: first the incisive suture, than the posterior part of the median palatine suture, followed by the transverse palatine suture and finally, the anterior part of the median palatine suture.

k The incisive suture is very particular and very different from the other three palatine sutures. It begins its fusion around the age of 16, and is completely fused by the age of 25 years. However, it may persist near the incisive foramen, very piecemeal and no more as a vestigial signature.

l. The anterior part of the median palatine suture gives very poor results, by opposition of the posterior part of the same suture, which is useful. We probably find an explanation by the fact that the anterior part is difficult to read, because of the appearance of *tori* and because this part is more inconstant in progression.

m. Concerning the posterior part of the median palatine suture, its dorsal subpart, near the inferior nasal spine, is always ahead of at least one degree of fusion from its ventral segment (which joined the staurion).

n. The evolution of the palatine sutures is carried out according to a centripetal procedure for incisive and transverse sutures, and to a dorso-ventral procedure for the two subparts of the median palatine suture (posterior and anterior segments, Fig. 4).

o. Internasal, intermaxillary and zygomaticomaxillary sutures are more reliable than other **fronto-naso-maxillary and zygomatic sutures**.

p. Internasal and temporozygomatic sutures fuse very slowly (on average 50 % of our elderly and very elderly people).

q. Nasomaxillary, frontonasal, frontomaxillary and frontozygomatic sutures are fused in the range of 40 % for the same sample.

5. CRANIAL SUTURES, THE PRESENT AND THE FUTURE.

Evolution of sutural fusion and medical imaging

It is easy to note that cranial sutures, even if they are a very old method of age estimation as highlighted by our historical approach, still retain a significant interest considering recent publications (XANTHOPOULOU *et al.*, 2018; ZVYAGIN & ANUSHKINA, 2018; SHEDGE & KANCHAN, 2019; FAN *et al.*, 2020; RUENGDIT *et al.*, 2020) and new applications, particularly according to target populations (China, Greece, Japan, Thailand, etc.).

For example, the CT-Scan and the simple quotes (open, partially closed, closed sutures) used by Boyd *et al.* (2015) to clearly differentiate the subjects into three groups (< 40 years; average

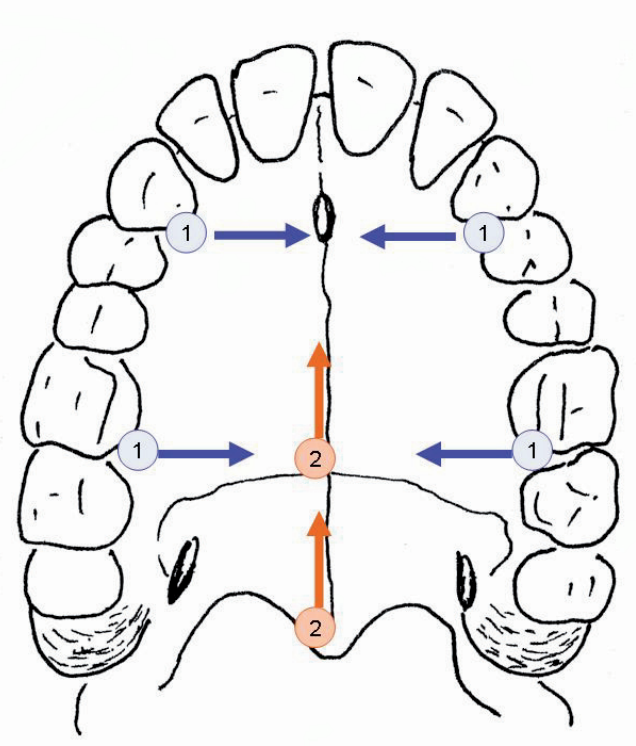


Fig. 4 - Palatine sutures, caudal view of the osseous palate. Direction (progression) of the segmental fusion. Drawing: © J.-P. Beauthier.

age; > 60 years). This approach, although being very simple, can provide some help during the discovery of isolated skulls in forensic context.

The complexity of sutural observation also directed researchers towards the use of thin sections FPCT (flat-panel computed tomography; HARTH *et al.*, 2010). Such a practice provides to complete the simple visual observation.

Reversed panoramic radiography of the lambdoid suture proved to be a very promising technique (CHANDRA *et al.*, 2015). It is true also for the digital approach to maxillary sutures among the Thai population by Sinthubua *et al.* both in terms of age (2016) and sex (2017).

In this Thai population, the study of cranial sutures leads to an overestimation of the age in young people, and an underestimation in the elderly. On the other hand, the study of maxillary sutures essentially based on the Mann method (MANN *et al.*,1991) gives excellent results, close to 100% (RUENGDIT *et al.*, 2018). The morphology (angled / curved) of the zygomaxillary suture in the cranial assessment of ancestry is of limited use (MADDUX *et al.*, 2015).

The bone impedance in assessing the degree of closure of the sagittal suture is worth mentioned (ISHIKAWA *et al.*, 2015).

As we already pointed out (BEAUTHIER, 2009), a few variables conduct disturbing the analysis, however, since the sutural fusion nevertheless keeps a fairly random evolution that is difficult to understand.

We note two reasons:

i. the first relates to a difference between endocranial and ectocranial fusions, hence the interest of the above-mentioned recent studies (HARTH *et al.*, 2010).
   It seems logical to think that this difference is related to dural endocranial contact, and we know that the *dura mater* products some growth factors (OPPERMAN *et al.,* 1995; OPPERMAN, 2000; BEAUTHIER, 2009);
ii. the second one relates to the complex interdigitations of the sutural regions, particularly at the lambdoid suture. We compared this architectural organization to the aspect of tectonic plates collisions and overlapping ice rafts when they drift and collide (MASHAAL, 2007).

Obviously, the methods using several methods (pubic symphysis, auricular surface) remain all their importance with better results concerning the hip bone compared to the sternal end of the 4th rib and cranial anterolateral sutures (GOCHA *et al.*, 2015), while specifying the poor efficiency of the pubic symphysis and cranial sutures among the elderly (XANTHOPOULOU *et al.*, 2018). A final approach not to be overlooked is the digital pelvic analysis (VILLA *et al.*, 2019).

Persons identification and medical imaging

An original aspect must be underlined, is namely the use of cranial sutures in the identification of the person. Rogers and Allard (2004) note that there is no sutural symmetry in the same individual, nor any comparison of one individual to another, even with homozygous twins. Sekharan (1987) even points out that the probability of finding an identical *pars lambdadica* in two individuals is 1/10,000[100].

The criteria allowing the good comparison and thus identification require that the image (RX, CT or MRI) are taken under the same conditions, without distortion, to study the sutures with sutural sections by taking visible reference points (e.g. the lambda) and obtain a minimum of the same four sutural lines in the same suture (BEAUTHIER, 2009).

According to Smith *et al.* (2002), the CT-Scan approach allows excellent sutural visibility and therefore this methodology is more valid in terms of identification than simple X-rays comparison. The same methodology could be applied to the MRI approach (see below).

Altered skulls and cranial sutures

In case of highly altered skulls, particularly when exposed to fire, sutural observation can still prove useful in identification, but in addition to other techniques, at least if bone layers (internal and / or external) are still present and have not

suffered too much from the thermal degradation. Remember that the intense heat can lead to real explosions of the cranial vaults, in addition to extensive intracranial (epidural) *post mortem* blood collections (BEAUTHIER, 2011).

Cranial sutures and fractures

A fundamental point is to identify normal sutures and differentiate these sutures from vault fractures. Sutures (but also other channels such as for arteries and cranial nerves) have blunted corticated margins and inter-digitations while "recent fractures have a sharper edge and can pass through existing sutures although not through recent prior fractures, which can help interpret the order in which fractures have occurred" (MADEA, 2020). We should quote too the study about rupture stresses and risk of fracture in the sagittal suture, with notable differences related to sex (TORIMITSU *et al.*, 2015).

We therefore proposed a detailed review of our observations of cranial and facial sutures, by studying various aspects such as primarily the age at death estimation, but also the great difficulties encountered in forensic anthropology in the approach of persons identification, when the skull is the only skeletal part entrusted to the analysis.

We have also discussed the considerable importance of medical imagery in the modern study of these sutures.

It also seemed essential to raise the major expert's difficulty when examining the skull: is it a suture or a fracture with all the judicial implications this differential diagnosis can generate? Finally, the scrupulous examination of the cranial sutures clearly retains all its current interest.

6. CONCLUSION

We proposed a study of the evolution of cranial sutures, as vault as viscerocranium, in order to help the physical anthropologist or the forensic anthropologist in estimating the age at death, according to a relatively simple but useful method.

However, it should well consider that this approach is certainly not the first method of this estimation.

We have also established a methodological framework based on the age classes (also free accessible).

There is detailed primacy of odontology and study of epiphyseal regions in juvenile long bones. The spheno-occipital synchondrosis as also its value, closing with an average around 20 years (the closure can be observed earlier in women at the age of 15 years in some cases; and later in men, which reach 24 years of age (MIRITOIU & SOFICARU, 1999; SCHEUER & BLACK, 2004; FEREMBACH *et al.*, 1979).

In young and middle adult, the pubic symphysis, the 4th rib and the auricular surface of the hip (coxal) bone are essential. Difficulties arise in the old and very old adult.

This is where our modestly sutural approach (including viscerocranial sutures with late and very late obliteration, and essentially the palatal sutures).

The bone histology (with counting of Haversian canals and remained free areas) is also very valuable, but destructive (MAAT *et al.*, 2002).

As we have already pointed out, the cranial sutures are still a rather random approach of the age at death, and caution must remain present.

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