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ORIGINAL ARTICLE

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Age estimation by cranial suture using postmortem computed tomography images among Malaysian

Malezyalılar arasında postmortem bilgisayarlı tomografi görüntüleri kullanılarak kranial sütür ile yaş tahmini

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ABSTRACT
Introduction: *In the forensic context, cranial sutures are valuable in the determination of age at death.*
Purpose: *This study was conducted to review the Meindl and Lovejoy's (ML) age estimation method in cranial suture from post-mortem computed tomography (PMCT) Digital Imaging and Communications in Medicine (DICOM) images among the Malaysian population.*
Material and Methods: *About 106 scanned cases by PMCT between year 2015 and 2018 at the institute were analysed upon fulfilling the inclusion and exclusion criteria. The estimated age was formulated by the ML scoring method. The total scores from combinations of seven different suture areas were analysed for correlation with age and its regression formula was applied for cross-validation study with actual age in terms of bias and inaccuracy.*
Results: *The sex and race contribute no measurable bias towards the age prediction. There was significant correlation between the total scores of cranial suture closure pattern and age. Results showed that the ML scoring method was useful for age estimation, in which 62.3% of cases were accurately estimated within standard of estimation error (SEE) range as well as the ML reference age range. There was a relatively good association between cranial suture closure pattern and age using the vault system by the ML method on PMCT DICOM images of the crania.*
Keywords: *Cranial Sutures, Forensic Anthropology, Meindl and Lovejoy, PMCT, Age Estimation*

ÖZET
Giriş: *Adli bağlamda, kranial sütürler ölüm yaşının belirlenmesinde değerlidir.*
Amaç: *Bu çalışma, Malezya popülasyonunda post-mortem bilgisayarlı tomografi (PMBT) Dijital Görüntüleme ve Tıpta İletişim ("Digital Imaging and Communications in Medicine"-DICOM) görüntülerinden kranial sütürde Meindl ve Lovejoy'un (ML) yaş tahmin yöntemini incelemek için yapılmıştır.*
Gereç ve Yöntem: *Enstitüde 2015 ve 2018 yılları arasında PMBT tarafından taranan yaklaşık 106 vaka, dahil etme ve hariç tutma kriterlerini yerine getirdikten sonra analiz edildi. Tahmini yaş, ML puanlama yöntemiyle formüle edildi. Yedi farklı sütür alanının kombinasyonlarından elde edilen toplam puanlar, yaşla korelasyon için analiz edildi ve yanlılık ve yanlışlık açısından gerçek yaş ile çapraz doğrulama çalışması için regresyon formülü uygulandı.*
Bulgular: *Cinsiyet ve ırk, yaş tahminine yönelik ölçülebilir bir önyargıya katkıda bulunmaz. Kranial sütür kapanma paterni toplam puanları ile yaş arasında anlamlı bir ilişki vardı. Sonuçlar, ML puanlama yönteminin, vakaların %62,3'ünün standart tahmin hatası (SEE) aralığının yanı sıra ML referans yaş aralığı içinde doğru bir şekilde tahmin edildiği yaş tahmini için yararlı olduğunu göstermiştir. Kafatasının PMBT DICOM görüntülerinde ML yöntemiyle tonoz sistemi kullanılarak kraniyal sütür kapanma paterni ile yaş arasında anlamlı bir ilişki olduğu sonucuna varıldı.*
Anahtar Kelimeler: *Kranial Sütürler, Adli Antropoloji, Meindl ve Lovejoy, PMCT, Yaş Tahmini*

INTRODUCTION

Age estimation in forensic anthropology was imperative in the identification but presented with great challenges predominantly in the adult remains (1). There were documented age indicators that may include cranial suture closure, dentition, ossification centres and epiphysis as well as the articulating surfaces of auricular surface and pubic symphysis (2). In the forensic context, cranial sutures were valuable in the determination of age at death because the cranium

of skeletonised remains was commonly well-preserved (2-3). For nearly a century, cranial suture closure pattern was frequently used as an age indicator among many investigators including the recent use of imaging modalities such as computed tomography (CT) (1,3). The closure of suture has a sequence of fusion and it can be correlated to its age. For instance, vault sutures that refer to sagittal, coronal and lambdoid sutures exhibit progressive closure from mid-twenties. The degree of closure shown by these sutures was well associated with the age at death. The sutures were easily observed in the young adults but more or less obliterated in the skull of elderly (4).

Since the publication of Todd & Lyon's landmark study in year 1924 on endocranial suture closure, some skeletal biologists have recurrently expressed concern on the accuracy of estimating age at death from the sutures due to the phenomenon of "lapsed union". Meindl & Lovejoy eventually revived the use of cranial sutures in age estimation with a study involving samples of 236 crania from a collection of Hamann-Todd (5). They concluded that ectocranial sutures could estimate age at death with fair accuracy, and ectocranial sutures are more precise than endocranial sutures. Their method was widely used by forensic anthropologists who working with modern populations due to its practical approach and the fact that ectocranial fusion was more closely related towards extreme age for which forensic standards were most desired although with great intra-sutural variability observed along its length (3).

Furthermore, Stephen & Carlos has also indicated that bias became negative in the 40s, suggesting that the Meindl & Lovejoy aging method becomes less valid by middle age & deviates widely by older age (6). Firstly, they concluded that correlations between suture closure and age were relatively similar between the Hamann-Todd and Terry Collections but were remarkably lower for the modern samples. Secondly, the lateral anterior system of suture sites was not better than the vault system in age estimation, contradicting findings of Meindl & Lovejoy (1985). Thirdly, significant deviation in the rate and pattern of suture closure was noticed between sex as well as ancestry subgroups, again contradicted Meindl & Lovejoy (1985) and Millard (2011) (7). The overall degree of error for the Meindl & Lovejoy aging method was not much different from other macroscopic skeletal aging techniques and strongly underestimated the age of the modern samples (3,6).

In a study by using 175 Thai dry cranial bones, Acsádi and Nemeskéri (1970), Meindl & Lovejoy (1985), and Mann (1991) methods were studied (8). These methods have led to under-estimation among older individuals and over-estimation among young adults with a big inaccuracy range of 13 to 22 years. Another study showed that endocranial suture fusion was detected as early as 21 to 30 years and found to be more consistent than ectocranial fusion (9).

There were several studies conducted based on radiological imaging approaches. Imran et al. (2017) elaborated that closure starts for each suture within 33 years in females and 31 years in males (10). They reported that coronal suture was started to fuse earlier followed by sagittal and then lambdoid suture. Pardeep et al. (2014) revealed that age of earliest fusion for lambdoid and coronal ectocranial sutures were at 40 years while for parieto-mastoid and squamous sutures were at 45 years (11). Age of fusion for lambdoid and coronal sutures were at 45 – 50 years while for parieto-mastoid sutures at 55 – 60 years followed by squamous sutures at 60 – 65 years. However, throughout a preliminary analysis by Meindl & Lovejoy method, certain sutures were of restricted value for reliable age determination. Closure at parieto-mastoid suture was not clearly associated with age whilst the squamosal point gave the minimum amount of age-related information. Hence, both sutures were rejected from consideration (5).

Despite the agreement and disagreement from the thorough literature search, the benefit of our study was to assist the forensic pathologist, forensic anthropologist and forensic radiologist to check on the accuracy of the existing Meindl & Lovejoy method, which was commonly applied at the Institute, through the post-mortem computed tomography (PMCT) approach. This could enable them to perform age estimation through the scoring of ectocranial suture closure based on the PMCT images available without defleshing the unknown human remains. In this study, we aimed to determine the feasibility of Meindl & Lovejoy method using PMCT images of the ectocranial suture; to compute the accuracy of the Meindl & Lovejoy method in age estimation compared to the actual age as well as to study the relationship between scoring of ectocranial suture closure with the actual age by correlation and regression analysis.

MATERIAL AND METHODS

Sample selection

This was a retrospective cross-sectional study involving all postmortem cases that have been scanned using postmortem computed tomography scan in the year 2015 - 2018. Approximately equal numbers of 18 samples were selected from each of the decades for each sex (Male and Female) & ancestry subgroup (Malay, Chinese and Indian). The age distributions are fairly flat and unbiased with similar mean ages for each subgroup to avoid inter-subgroup deviation and to decrease error (6-7). Malaysians with ages at death ranged from the early 20's till the late 70's were included with the age group of 10 years old. Cases were excluded if any events that could have affected the cranial sutures and

Table 1: Meindl & Lovejoy's Method of Age Estimation from Cranial Suture Closure

Total Composite Score Range	Meindl & Lovejoy's Age Range (Years)
0	<49
1-2	19-44
3-6	23-45
7-11	28-44
12-15	31-65
16-18	35-60
19-20	34-63
21	>43

its ossification including skull fracture, burning, cranial anomalies such as stenocephaly or diseases.

Post-mortem Computed Tomography (PMCT)

A native PMCT scan was executed within six hours upon receiving the dead bodies to the Institute. PMCT scanning was completed prior to any manipulation of the deceased using a 64-slice multi-detector CT scanner (Toshiba Aquilion 64 TSX-101A, Japan) that was dedicated for autopsy cases. Examinations were started from head to toe in a cranio-caudal direction by using 1mm slice thickness for the head region while 2mm slice thickness for the rest of body parts. Scans were executed using pre-defined scanning protocols: 120 kVp, Auto set mAs (Caredose), FOV 500 (LL), 1.0 x 32 raw detector collimation and 0.844/standard pitch. Curved Multiplanar reformatted (MPR) and three-dimensional (3D) image reconstruction of images involving the entire cranium was done and viewed using bone window on the Osirix workstation.

Meindl and Lovejoy's Method

The Meindl & Lovejoy Method established estimation of age at death by assessing the obliteration level of each ectocranial suture. Study was using seven ectocranial landmarks (1-cm long areas of suture at each landmark) that scored on the right side only for each skull. This was due to no significant bilateral variation found in cranial suture closure in a single individual within a specific age range (12). As shown in Figure 1, each landmark was assessed by assigning a closure scoring value on a 4-point scale (from zero to three), starting from completely opened suture (zero), minimal closure with less than 50% obliteration (one), significant closure with more than 50% obliteration (two), or complete obliteration (three). Once each ectocranial suture was assessed, scores are summed to calculate a composite score, which was then used to allocate an interval of age estimation as shown in Table 1 (3,5). Figure 2 were adopted from Fumiko et al. (2013) based on the PMCT images of the cranial suture scoring (1).

Cranial suture sites

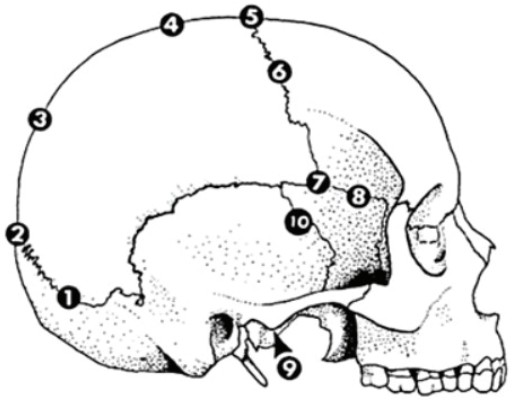

Figure 1: Landmark of Cranial Sutures adopted from Meindl and Lovejoy (1985) (8)

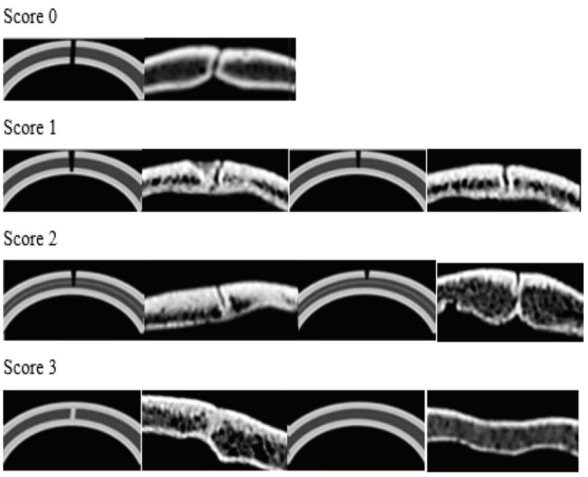

Figure 2: Scoring Diagram adopted from Fumiko et al. (2013) (2)

Figure 1 and Table 2 showed the ectocranial suture observation sites (5). The first 7 of these sutures would be referred to as the vault system. The subsequent 3 combining with pterion and mid-coronal would be classified as the lateral-anterior system (5). However, we focused on the vault system due to observer's limitation during our pilot study whereby we have found that only the vault system was feasible to be studied using Meindl and Lovejoy's scoring method through PMCT DICOM images of the cranial sutures. This was because observers discovered that it was very difficult to locate and identify the lateral anterior system i.e. sphenoid-frontal and sphenoid-temporal sutures especially when they were completely obliterated.

Data collection and analysis

First of all, all postmortem cases were retrieved from the PMCT database system based on inclusion by age groups and exclusion criteria. All images were assessed by a single observer based on the protocol; subsequently inter-observer and intra-observer reproducibility were verified by randomly selecting 30% of subjects for re-evaluation by both observers during our pilot study

Table 2. Description of Cranial Suture Sites

No.	Suture Sites	Description
1	Midlambdoid	Midpoint of each half of the lambdoid suture (in "pars intermedia" of the lambdoid suture)
2	Lambda	At lambda (in "pars lambdica" of sagittal and "pars lambdica" of lambdoid sutures)
3	Obelion	At obelion (in "pars obelica" of the sagittal suture)
4	Anterior Sagittal	Point on the sagittal suture at the juncture of the anterior one-third and posterior two-thirds of its length (usually near the juncture of the "pars bregmatica" and "pars verticis" of the sagittal suture)
5	Bregma	At bregma (at "pars bregmatica" of the coronal and "pars bregmatica" of the sagittal sutures)
6	Midcoronal	Midpoint of each half of the coronal suture (in "pars complicata" of the coronal suture)
7	Pterion	At pterion, the region of the upper portion of the greater wing of the sphenoid, usually the point at which the parietosphenoid suture meets the frontal bone
8	Sphenofrontal	Midpoint of the sphenofrontal suture
9	Inferior Sphenotemporal	Point of the sphenotemporal suture lying at its intersection with a line connecting both articular tubercles of the temporomandibular joint
10	Superior Sphenotemporal	Point on the sphenotemporal suture lying 2 cm below its juncture with the parietal bone

by using Wilcoxon Signed-rank test (1). Average score would be considered in the observer analysis. Estimated age was computed using Meindl and Lovejoy's composite scoring method by referring to its constructed reference age range and comparing with the actual age of the deceased to determine the accuracy rate. Accuracy rate was computed as the percentage of cases whereby actual age fell within the estimated range. New interdecile range (CI: 80%) was reconstructed based on the interdecile range between first and ninth decile of the actual age that fell into the respective determined score range.

Normality test was performed to determine the normal distribution of the data including the actual age, estimated age and total scores. Relationship between scoring of cranial suture closure with the actual age was determined by using correlation analysis via software SPSS version 26.0 so as to form a regression formula based on Meindl and Lovejoy's vault system method. The estimated age through the regression formula with standard of estimation error (SEE) applied among Malaysian individuals were computed to compare with their actual ages, followed by the analysis of bias and inaccuracy to assess the reliability of the formula. Bias was defined as the mean of error in predicting age whether under or over estimation whilst inaccuracy was defined as the average of absolute error of age estimation in modulus, regardless of over or under prediction. The formulae of bias and inaccuracy were as the following Ruengdit et al. (2018) (13).

$$\text{Bias} = \sum (\text{estimated age} - \text{actual age})/n$$

$$\text{Inaccuracy} = \sum |\text{estimated age} - \text{actual age}|/ n$$

Ethical clearance

Prior to the conduct of this study, we have obtained ethical approval from the Medical Research & Ethics Committee (MREC) despite only retrospective data retrieved for analysis without any clinical intervention in this study. Subject privacy would be protected during data collection as only postmortem number would be captured, the data would be kept in softcopy by only the principal investigator and would subsequently be destroyed at the end of the study.

RESULTS

Based on the randomly selected 30% subjects for the inter-observer variability in our study, we have discovered that there was no significant difference in term of total scores for suture closure between both observers at $p>0.05$ based on Wilcoxon Signed-rank analysis. There was also no significant difference for each individual landmark at $p>0.05$ using the same statistical test. In terms of intra-observer analysis, there was also no significant difference for all the landmarks and total scores between the duplicate scorings within the same observer at $p>0.05$ based on Wilcoxon Signed-rank analysis.

We also have computed the accuracy of the Meindl and Lovejoy's method in age estimation compared to the actual age. Based on our study, we discovered that there were 62.3% of the cases accurately being estimated whereby the actual age fell into the estimated reference

Table 3: Mean age and mean total score based on sex and races

Sex	Races	Mean Age (Years)	Mean Total Score
Male	Malay	47.11	17.89
	Chinese	49.61	18.00
	Indian	47.24	17.00
Female	Malay	48.32	18.05
	Chinese	50.94	18.67
	Indian	46.25	17.94

Table 4: Reconstructed age range based on the total composite score

Total Composite Score Range	Reconstructed Age Range (Years)
7-11	<33
12-15	22.0 – 59.6
16-18	23.0 – 67.0
19-20	26.0 – 73.7
21	>35

Table 5: Descriptive statistics of the estimated age on the vault cranial sutures via the Meindl and Lovejoy's method in the Malaysian population through the generated regression formula of this study

Age group (year)	Actual Age				Estimated age			
	n	Mean	SD	Range	n	Mean	SD	Range
20 – 29	18	23.3	2.8	19 - 29	18	44.3	8.5	24.8 – 55.1
30 – 39	18	35.0	2.4	31 - 38	18	45.5	7.8	27.0 – 55.1
40 – 49	20	44.8	2.5	40 - 48	20	49.6	4.9	36.5 – 55.1
50 – 59	18	54.9	2.7	50 - 59	18	49.8	4.4	38.8 – 55.1
60 – 69	18	62.8	2.6	60 - 67	18	49.4	4.5	41.1 – 55.1
≥70	14	75.4	2.6	70 - 84	14	52.1	3.2	45.8 – 55.1
Overall	106	48.3	17.0	19 - 84	106	48.3	6.4	24.8 – 55.1

Note: n = number of cases, SD = standard deviation.

age range using Meindl & Lovejoy method.

Mean of total score and mean age based on sex and race of this study were shown in the Table 3 with the assumption of the normal distribution of the data. Based on the univariate analysis in our study, there was no significant interaction effect that influence the total score of cranial suture, $F(6,105) = 0.05$, $p>0.05$ for sex*race and it was even true at $p>0.05$ with single factorial analysis either by sex or race.

We also have reconstructed the new interdecile range (CI: 80%) for age estimation based on our samples selected in this study as shown in Table 4. However, the usefulness and practicality of this estimated age reference ranges could be very limited due to its extremely bigger range up to the gap of 40 years old compared to other age estimation methods especially dentition in which can be narrowing down towards range of few months old in adolescents and few years old in adults.

We have noticed that there was a significant positive relationship between total scores of cranial suture closure with the actual age by correlation analysis, $r(105) = .370$, $p<0.05$ although it was just at relatively medium-strength level. In addition, most of the individual landmarks except Obelion and Pterion were correlate well with actual age. In other words, these two sutures were both not the good indicators for age estimation based on scoring of cranial suture closure. From the regression analysis, we could deduce a formula Age = 2.33*Total Score + 6.19 with the standard error of estimation at 15.9 years old, $r = 0.37$ and $R2 = 0.14$, $p< 0.001$. Descriptive statistics of the estimated age from the Meindl & Lovejoy vault system method applied on Malaysian individuals were calculated by using the regression formula to compare with their actual ages as summarized in Table 5.

This method of the generated regression formula showed an over-estimation of age among individuals aged less than 50 years. In contrast, the method has under-estimated the age in older individuals over 60 years. However, there was an association between the estimated age and actual age at $r = 0.374$, $p<0.001$. Bias and inaccuracy obtained were displayed in Table 6. Similar results were observed whereby an over-estimation of age for individuals aged below 50 years and under-estimation for individuals above 60 years of age, for both females and males as well as in the overall population. The bias of this method was found to be lower in males than in females. The inaccuracy was slightly higher in males compared to that in females. In the overall age and sex groups, this method tended to slightly over-estimate the estimated age with bias of 0.1 years with 12.6 years of inaccuracy.

DISCUSSION

The individual aging process was determined by complex interaction factors between genes,

Table 6: Bias and inaccuracy in estimating age on the vault cranial sutures via the Meindl and Lovejoy's method in the Malaysian population through the generated regression formula of this study

Age group	Male			Female			Total Cases		
(year)	n	Bias	Inaccuracy	n	Bias	Inaccuracy	n	Bias	Inaccuracy
20 – 29	9	21.5	21.8	9	20.3	20.3	18	21.0	21.1
30 – 39	9	9.1	9.7	9	12.0	13.5	18	10.5	11.6
40 – 49	10	4.1	6.1	10	5.7	6.2	20	4.9	6.1
50 – 59	9	-2.8	3.6	9	-7.4	7.4	18	-5.1	5.5
60 – 69	9	-14.9	14.9	9	-11.9	11.9	18	-13.4	13.4
≥70	7	-22.1	22.1	7	-24.5	24.5	14	-23.3	23.3
Overall	53	-0.2	12.9	53	0.3	12.4	106	0.1	12.6

Note: n = number of cases.

environment, and culture that may influence aging and create a gap between chronological and physiological age. This will lead to skeletal aging becoming an inconstant and non-linear process. The best practice in estimating the age at death was the population-specific method if it was available (14). Hence, this study was done to establish the method's reliability and to analyse for any difference between estimated age and actual age in the Malaysian population.

Milliard, (2011) showed that intra-observer error rates were greater at respective individual suture sites whereby the error rates for the vault and lateral-anterior systems were only 10% and 20% respectively (7). This study, however, there was no statistically significant difference in both the intra-observer and inter-observer scoring concurred with Fumiko et al. (2013) (1).

Fumiko et al. (2013) conducted a study to examine PMCT images of 125 subjects whereby the sagittal suture was divided into 4 segments and twenty cross-sectional slices within 10-mm block from each segment were then analysed (1). They have discovered a positive association between closure degree and age in which concurred with the findings of our study.

Furthermore, Fumiko et al. (2013) also showed that there was a statistically significant difference in the progression of suture closure degree between males and females (1). The suture obliteration would be set a bit earlier and proceeds slower in the females than in males (4). Despite that, our study showed that there was no significant of such interaction effect. Hence, we also agreed with the other authors that race and sex contribute no measurable bias to age estimation as well as the estimates of variance in error of prediction. This was deduced from the similar distribution ratio of accuracy rate within sex and race groups (5).

Generally, the bias when applying the regression formula deduced from the Meindl and Lovejoy's composite scoring method tends to over-estimate the age in younger individuals and under-estimate the age of older individuals. This was consistent with those findings found in the studies by Ruengdit et al. (2018) on Thai population, Wolff et al. (2012) on the Hungarian population and Galera et al. (1998) on Terry Collection (13,15-16). However, the cut-off point of the over-age and under-age estimation pattern was found to be different. This study was consistent with that in the Hungarian population whereby over-estimation of age was presented when the method was conducted in individuals below age of 50 years whilst under-estimation was observed in persons above age of 60 years,. However, the cut-off point for under-estimation of age in the elderly was 50 years old in the Terry Collection and over-estimation of age in young adults was 40 years old in the Thai population.

The inaccuracy value obtained in this study was stated to be lower when comparing with the inaccuracy of the studies in the Thai population, Terry Collection and Hungarian population (13,15-16). This could be attributed to the use of PMCT scan in this study that allowed a better assessment of the closure of the sutures as compared to the conventional age estimation method via the observation on dry skulls. Similar to that in other studies, the inaccuracy values were enlarged when analysed in elderly people indicating that the efficacy of the method had significantly declined in advanced-age groups. Regardless of reference and target samples, the estimation error remains as the main challenges of all conventional age estimation methods for decades, particularly when dealing with elderly adults (17).

The accuracy rate yielded from the generated regression formula was considerable, given that 62.3% of actual ages fell into the estimated age range at SEE ±15.9 years old. This might be acceptable for use in forensic circumstances due to its lower bias and inaccuracy. However, this accuracy rate of 62.3% did not concur with the confidence interval (80%) of interdecile range given by Meindl & Lovejoy (1985) (5). Sittiporn et al. (2018) stated that the inter-population variation did exist on the suture closure, conforming to the necessity to use population-specific standards due to interaction

of factors between genes, environment, and culture (8). Although this method is not superior to the traditional aging methods when applied to Malaysian population, it might still be considered as it allows an assessment of age without the need to remove the soft tissues. It should be utilised in conjunction with other adult age estimation techniques to arrive at a narrow estimated age range. However, the usefulness and practicality of these estimated age ranges would be enhanced further with the use of expanded sample size in future studies.

CONCLUSION

The vault system was feasible to be studied using Meindl and Lovejoy's method through PMCT DICOM images of the cranial suture. We concluded that the race and sex contribute no measurable bias towards the age estimation. The accuracy of the Meindl and Lovejoy's method with its reference age range compared to the actual age in this study was 62.3% that lower than its confidence interval of interdecile range at 80%. Despite that, cranial suture closure total composite score was relatively correlated well with the actual age except the individual landmarks of Obelion and Pterion. Regression formula generated from this study, with accuracy of 62.3%, could be more useful than the new interdecile range generated for each category of composite score.

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