Brief Communication:

Timing of spheno-occipital closure in modern Western Australians

Daniel Franklin[1], PhD

Ambika Flavel[1], MSc

[1]Centre for Forensic Science, The University of Western Australia, 35 Stirling Hwy, Crawley, Western Australia.

Correspondence

Daniel Franklin
Centre for Forensic Science
The University of Western Australia
M420, 35 Stirling Highway, Crawley, 6009
Western Australia

Ph. +61 8 6488 1232
Fax. +61 8 6488 7285
Email daniel.franklin@uwa.edu.au

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Abstract

The spheno-occipital synchondrosis is a craniofacial growth centre between the occipital and sphenoid bones – its ossification persists into adolescence, which for the skeletal biologist, means it has potential application for estimating subadult age. Based on previous research the timing of spheno-occipital fusion is widely variable between and within populations, with reports of complete fusion in individuals as young as 11 years of age and non-fusion in adults. The aim of the present study is, therefore, to examine this structure in a mixed sex sample of Western Australian individuals that developmentally span late childhood to adulthood. The objective is to develop statistically quantified age estimation standards based on scoring the degree of spheno-occipital fusion.

The sample comprises multi-detector computed tomography (MDCT) scans of 312 individuals (169 male; 143 female) between 5 to 25 years of age. Each MDCT scan is visualized in a standardized sagittal plane using three-dimensional oblique multiplanar formatting and fusion status is scored according to a four-stage system. Transition analysis is used to calculate age ranges for each defined stage and determine the mean age for transition between an unfused, fusing and fused status. The maximum likelihood estimates for the transition from open to fusing in the endocranial half is 14.44 years (male) and 11.42 years (female); transition from fusion in the ectocranial half to complete fusion is 16.16 years (male) and 13.62 years (female). This study affirms the potential value of assessing the degree of fusion in the spheno-occipital synchondrosis as an indicator of skeletal age.

A routine analysis of human skeletal remains will inevitably require an estimation of age-at-death. The manner in which that information is interpreted varies according to specific requirements. In a forensic context it is important towards establishing personal identity (Komar and Buikstra, 2008), whereas in an archaeological context it provides demographic information useful for interpreting the health of past populations (Hoppa, 2002). For the analysis of skeletal remains encompassing the juvenile to early adolescent lifespan, there are numerous methods available to the anthropologist to facilitate an estimation of age. The latter is inherently related to the availability of many predictable and well-documented developmental markers in the immature skeleton (Scheuer, 2002). Of those developmental markers, it is widely acknowledged that the dentition (specifically tooth formation and eruption) is generally the most accurate characteristic upon which to derive an estimation of age (Olze et al., 2005; Reppien et al., 2006). It is also possible to accurately estimate age based on an assessment of skeletal maturity; this is a developmental measurement of bone size, shape and degree of ossification relative to full maturity (Franklin, 2010).

As highlighted in the 'Best Practices' section of the Age Estimation document produced by the Scientific Working Group for Forensic Anthropology, the reference data (standards – statistical data) used to formulate an estimation of skeletal age need to be appropriate to the ancestry/population origin of the remains examined (SWGANTH, 2013). It is also important to note that standards based on the analysis of temporally distant museum and university collections comprising individuals born in the 19th and early 20th Century are, in many instances, less likely to be representative of the same modern population. Where possible, therefore, age assessments should be performed using contemporary population-specific standards. The latter considerations, combined with rapidly advancing medical imaging technology, has seen an increasing number of studies providing age estimation standards for a variety of global populations (e.g., Dedouit et al., 2008; Bassed et al., 2011; Brough et al., 2012; Dedouit et al., 2012; Lottering et al., 2013). Medical scans offer an appropriate, reliable and arguably more representative source of contemporary population-specific data (Franklin et al. 2013).

The spheno-occipital synchondrosis is a cartilaginous craniofacial growth center between the occipital and sphenoid bones. Previous research indicates that fusion of this structure commences endocranially (initial sign of closure is a bony bridge in its superior part) and proceeds to the ectocranial surface (e.g., Powell and Brodie, 1963; Brodie, 1964; Ingervall and Thilander, 1972; Shirley and Jantz, 2011). It has a relatively late ossification in comparison to the other cranial base synchondroses that fuse prenatally (inter-sphenoid) or in early childhood (spheno-ethmoidal) (Scott, 1958; Hayashi, 2003). From the perspective of the forensic and/or physical anthropologist, the persistence of the spheno-occipital synchondrosis into adolescence means that it can be used to derive an estimate of subadult age; specifically an upper or lower age boundary depending on its stage of fusion (Shirley and Jantz, 2011).

The timing of spheno-occipital fusion, however, is widely variable in the literature, with reports of complete fusion in individuals as young as 11 years of age (Kahana et al., 2003). This is considerably earlier than traditionally held views in various anatomy texts suggesting that spheno-occipital fusion indicates the beginning of adulthood (e.g., Grant, 1947; Romanes, 1964). The latter sources, however, do not utilize powerful medical imaging modalities in common use today (e.g., computed tomography). An emerging point of commonality in recent literature utilizing imaging, rather than direct inspection approaches, is that spheno-occipital fusion frequently occurs in adolescence (Okamoto et al., 1996; Sahni et al., 1998; Shirley and Jantz, 2011).

Given the apparent variation evident in the timing of fusion of the spheno-occipital synchondrosis, the aim of the present study is to examine this structure in a sample of male and female individuals that developmentally span late childhood to adulthood. Based on previous research it is a realistic expectation that the onset of fusion will not be evident in young children, but it is important to determine the lower (and upper) age boundaries for the fusion of the synchondrosis. The primary objective is to develop statistically quantified age estimation standards, based on scoring the degree of spheno-occipital fusion as visualized in high-resolution multi-slice CT scans that have direct application in biological and forensic anthropology.

MATERIALS AND METHODS

The present study examines high-resolution cranial multi-detector computed tomography (MDCT) scans of 312 individuals between the ages of 5 and 25; 169 males and 143 females (Figure 1). The study sample comprises a random sampling of a contemporary Western Australian population drawn from a Picture Archiving and Communication Systems (PACS) database comprising patients presenting at various Western Australian hospitals for clinical cranial evaluation between 2010 and/or 2011. A stringent inclusion criterion was applied, whereby any CT scans presenting acutely abnormal morphologies resulting from trauma, pathology, congenital and/or developmental disorders (e.g. Turner's syndrome) were excluded. The majority of the CT scans included in this study have a slice thickness ≤1.5mm. Research ethics approval was granted by the Human Research Ethics Committee of the University of Western Australia (RA/4/1/4362).

MDCT scans are reconstructed using OsiriX® (version 3.9-64 bit). Visualization of the cranial base is performed using three-dimensional oblique multiplanar reformatting (MPR). Axial and coronal views are used to orientate the cranium into a standardized position to allow assessment of fusion status in the sagittal plane. The fusion status of the spheno-occipital synchondrosis is scored according to a four-stage system (Table 1 and Figure 2) modified from Bassed et al., (2010) and Shirley and Jantz (2011). As not all readers are familiar with the virtual visualization and assessment of skeletal structures in digital medical modalities, six individuals are presented as exemplars. Successive stages of spheno-occipital fusion are shown in the median sagittal plane in conjunction with reconstructions of the endo- and ectocranial macroscopic appearance of this structure (Figure 3). It is important to note that all assessments are only made using a three-dimensional oblique MPR visualization in the sagittal plane (see above).

All individuals were scored by both authors (DF and AF). Inter-observer error is quantified using Cohen's Kappa coefficient calculated using the scores assigned for the total sample (Cohen, 1968; Landis and Koch, 1977). The Kappa statistic provides a quantitative measure of the magnitude of agreement between observers (Viera and Garrett, 2005). Intra-observer error is calculated based on the repeated assessment of 50 individuals, with a 3-month interval left between the first and second scoring

sessions. Observer error and other descriptive statistics (e.g. mean age according to stage) are calculated using SPSS (version 19.0).

Transition analysis is used to calculate age ranges for each of the defined spheno-occipital stages. This parametric method is used to model "…the passage of individuals from a given developmental stage to the next higher stage in an ordered sequence" (Konigsberg et al., 2008:542). Transition analysis uses a log-age cumulative probit model to calculate the mean and standard error of the age of transition between the developmental phases (Kimmerle et al., 2008; Shirley and Jantz, 2011). Transition analyses are performed using the Nphases2 program (available at http://konig.la.utk.edu/nphases2.htm) – see Boldsen et al., (2002); Konigsberg et al., (2008) for detailed methods.

RESULTS

Based on the repeat assessment of 50 individuals both observers had a total of 3/50 non-agreements (different specimens – Table 2). The Kappa measure of agreement for DF and AF is 0.907 ($P < 0.001$); the strength of agreement between repeated observations is thus rated as 'almost perfect' (Landis and Koch, 1977). Inter-observer accordance based on the analysis of the total sample is 0.867 ($P < 0.001$) which also implies an 'almost perfect' agreement. For both the intra- and inter-observer assessments, there were no instances where the difference between repeated observations and/or observers differed by more than one stage.

Spearman rank correlations indicate a significant positive relationship between age and stage of spheno-occipital fusion for both sexes (male: $r_s = 0.855$; sig = $p < 0.001$ female: $r_s = 0.821$; sig = $p < 0.001$). The youngest age for attainment of stage 3 (complete fusion) is 13.42 years in males (mean 19.83 years) and 11.75 years in females (mean 18.62 years). The latest age at which fusion remains incomplete (stage 2) is 16.83 (mean 16.38) and 15.09 (mean 13.53) years for males and females, respectively (Table 3; and see Figure 4).

As there are four successive spheno-occipital fusion stages, a total of three transition distributions are modeled (Table 4; Figure 5). Following Shirley and Jantz (2011), 'unfused', 'fusing' and 'fused' age limits are derived from the upper and

lower bounds of stage transition distribution using ±1 and ±2 standard deviations, representing 68% and 95% of the prediction intervals respectively. The 'unfused' age limit is based on the upper age boundary and *vice versa* for the 'fused' age limit. The latter represent the oldest age at which an individual is likely to present non-fusion, and the youngest age of fusion, of the spheno-occipital respectively. The curves for stages 1 and 2 are also combined to provide the lower and upper 'fusing' age limits (Table 5).

DISCUSSION

The objective of the present study was to evaluate fusion timing of the spheno-occipital synchondrosis in a modern Western Australian population to establish age-at-transition standards and determine the lower and upper developmental age boundaries for this structure. This morphological characteristic is of particular interest to skeletal biologists because its development spans childhood to adolescence. The latter range is especially significant because this is an age where there are few other markers of skeletal development available for assessment.

The results of the intra- and inter-observer testing indicate that assignation of the developmental stages are reproducible both within and between observers (Table 2). Our results are overall comparable to that of Bassed et al., (2010), who in using a similar approach based on the assessment of CT images, demonstrated excellent agreement within individual observers (κ 0.907). Inter-examiner accordance in Bassed et al., (2010) was slightly lower than that of the present study (κ 0.780), albeit this is likely related to the fact that the former study used a 5-stage scoring system, which introduces an extra level of subjectivism, especially in cases where an individual could be classified as being in between two stages (e.g., fusion scar present or obliterated).

It was evident within the Western Australian population examined in the present study that spheno-occipital fusion begins earlier in females (by approximately 2 years) and that complete fusion of the synchondrosis occurred before 25 years of age. The 95% CI's for males and females respectively are 19.14–20.53 and 17.88–19.36 years. The latter findings generally accord with previous research (e.g., Powell and Brodie, 1963; Ingervall and Thilander, 1972; Sahnie et al., 1998; Shirley and

Jantz, 2011). The 95% PI transition ages for the fused stage are within 0.67 (male) and 0.99 years (female) of the data published by Shirley and Jantz (2011), based on their macroscopic analysis of a modern American population. In the analysis of a contemporary sample from the east coast of Australia, Bassed et al., (2010) demonstrated that spheno-occipital fusion is essentially complete by the age of 17 years in both sexes. In the present study, however, complete fusion occurred on average at 18.62 years of age in females and 19.83 years in males (Table 3). Although some degree of variation would be expected, any inferences regarding this disparity would require further investigation of a larger sample (see below).

In considering the forensic applicability of the data presented here, it was apparent that on average any individual, irrespective of sex, is less than 18 years of age if they present any evidence of a non-fused (or open) spheno-occipital synchondrosis. The range and/or 95% confidence interval values for the 'fusing' to 'fused' stages (1 to 3) are within the limits of other skeletal indicators (e.g., upper and lower limbs: Coqueugniot and Weaver, 2007; Cardoso, 2008; Cameriere et al., 2012; Saint-Martin et al., 2013). In the present study there is, however, extensive overlap between the age of transition distribution for the 'fusing' stages (Table 5), with values large enough to suggest due caution in attempting to use that data as a means of assessing the age of majority in this population. The primary issue is the relatively small number of individuals comprising Stage 2, and specifically the small difference in mean age for attainment of Stages 1 and 2 in females (Table 3). Further research is required to ensure the statistical robustness of these findings, however this is somewhat limited by the availability of suitable medical scans and/or dry bone specimens, which appears to be an issue encountered in similar previously published research (e.g. Bassed et al., 2010; Shirley and Jantz, 2011).

In further examining the small difference in mean age between Stages 1 and 2 in the female sample, it was evident that the majority of females assigned to Stage 2 were either borderline to the preceding stage and/or presented only a small amount of fusion greater than half the length of the synchondrosis – the minimum requirement for Stage 2. This is an issue inherent to any method that classifies a continuous maturity indicator (e.g. epiphyseal fusion) into an ordered (staged) system. One could attempt to mitigate this by incorporating extra fusion stages, for example scoring

fusion across the length of the synchondrosis according to quarters. The latter is analogous to the 'early' and 'late' phase stage systems used in adult age estimation methods (e.g. pubic symphysis – Brooks and Suchey, 1990). The inclusion of additional phases, however, may increase subjectivism in assessment, both within and between observers. A more practical solution is to increase sample size and capture the true range of variation within each phase, which can then be modelled using an appropriate statistical approach (e.g. transition analysis – c.f. Konigsberg et al. 2008).

Another important consideration of the present study, albeit one that is inherent to most studies based on the analysis of contemporary medical imaging modalities, is the lack of data concerning the specific ethnic mix of the population sample. In Australia research involving living individuals must follow the appropriate legislation (National Statement on Ethical Conduct in Human Research – NHMRC, 2013), which requires that the MDCT scans accessed are anonymised prior to receipt, with only sex and age information retained. Irrespective, there is no associated data regarding the ancestry of each individual because this information is not recorded when the patient presents for clinical evaluation as it is not deemed medically relevant. Based on the most recent census data from the Australian Bureau of Statistics (ABS, 2012) it is known that the Western Australian population is predominantly Caucasian in origin.

In further considering potential issues surrounding not knowing individual ethnicity, it has been suggested that the timing of skeletal maturation is actually more affected by the socioeconomic development of a population, rather than individual ethnic variation (e.g. Schmeling et al., 2000). Schmeling et al., (2005) also propose that the most relevant forensic age estimation studies are those that consider various ethnic groups of similar socioeconomic status living in the same region. The latter implies that disturbances to normal growth (and by association the timing of skeletal maturation) relating to nutritional deficiencies and/or chronic illness (amongst other potential factors) are likely to be less prevalent in a country of advanced socioeconomic standards, such as Australia (OECD, 2013).

The present study represents the first investigation of spheno-occipital synchondrosis fusion in a modern Western Australian population, which affirms the

potential value of evaluating this particular morphological characteristic for the purpose of estimating skeletal age in deceased and, where the situation arises, living individuals. The importance of performing anthropological assessments using appropriate contemporary population specific standards is an area of considerable interest in physical, and especially forensic, anthropology. This is especially imperative in circumstances where such assessments carry evidentiary weight in a court of law. To that end, it is strongly recommended that population-specific standards (where available) are used – this is also a 'best practice' guideline of SWGANTH (2013).

The data presented in this study is for the classification of contemporary Western Australian individuals. Although we are not implying that these statistics are not applicable to individuals from other Australian states and territories, their accuracy should be evaluated accordingly. The latter will require suitably large samples that are representative of the diverse Australian population and/or the combined analysis of extant data (e.g. Bassed et al., 2010) using the same scoring system(s) and appropriate statistical approaches. The assembly of such samples will afford novel insights into population variability across the country in relation to the timing of cranial growth and development. Lastly, it is important that the standards presented here are applied to radiographic and/or MDCT scans of the referred material or individual; this is because medical scans afford earlier detection, and arguably a more accurate interpretation, of fusion status compared to the gross examination of skeletal material (Shirley and Jantz, 2011).

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FIGURES

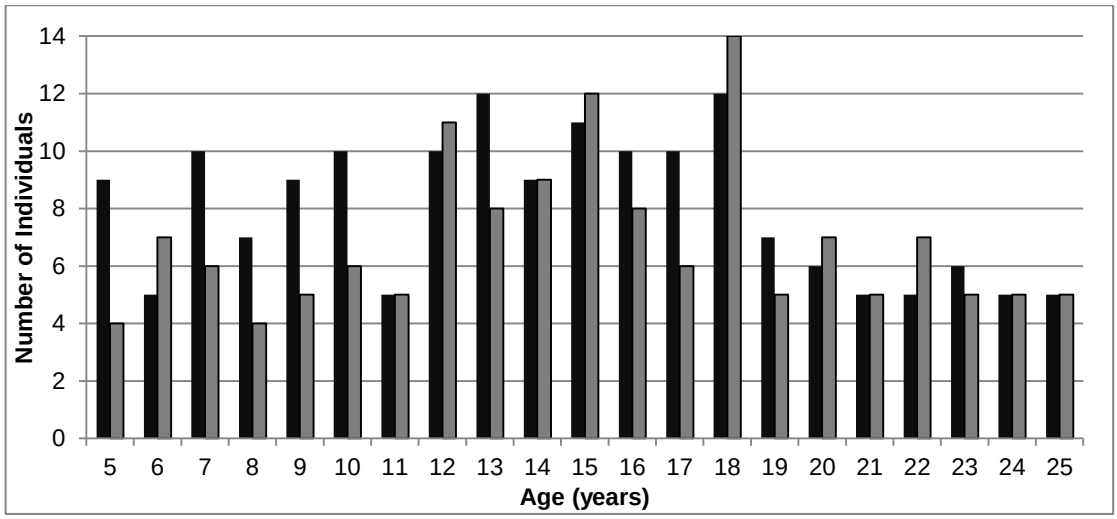

Figure 1. Age distribution of the Western Australian population – males (black bars); females (grey bars).

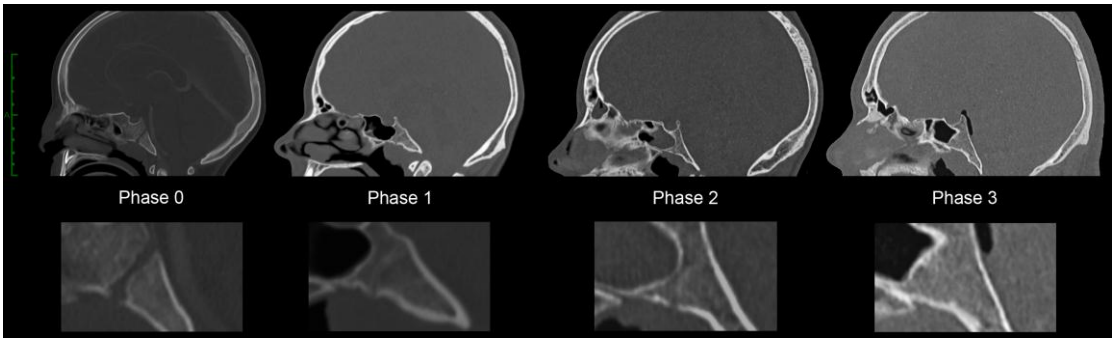

Figure 2. Stages of spheno-occipital synchondrosis fusion in the median sagittal plane (3D MPR reconstruction).

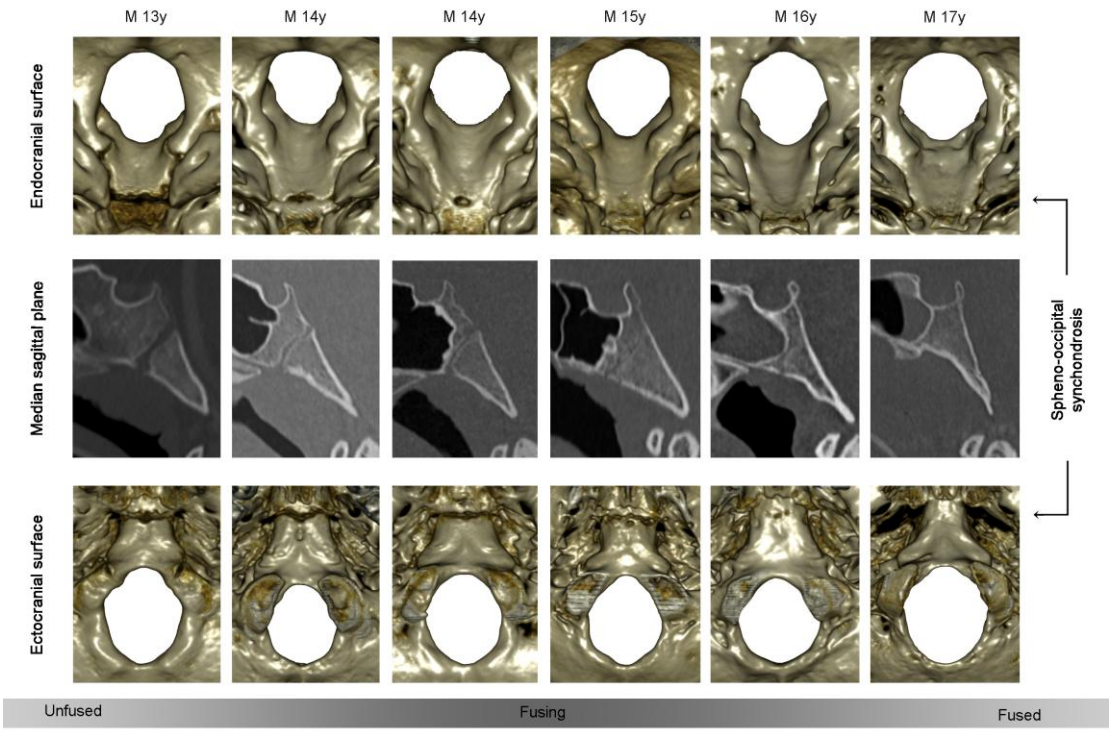

Figure 3. Endo- and ectocranial (3D volume reconstruction) and median sagittal (3D MPR reconstruction) views of the spheno-occipital synchondrosis at various stages of development. Note: data is cross-sectional whereby the associated images at each age represent a single individual.

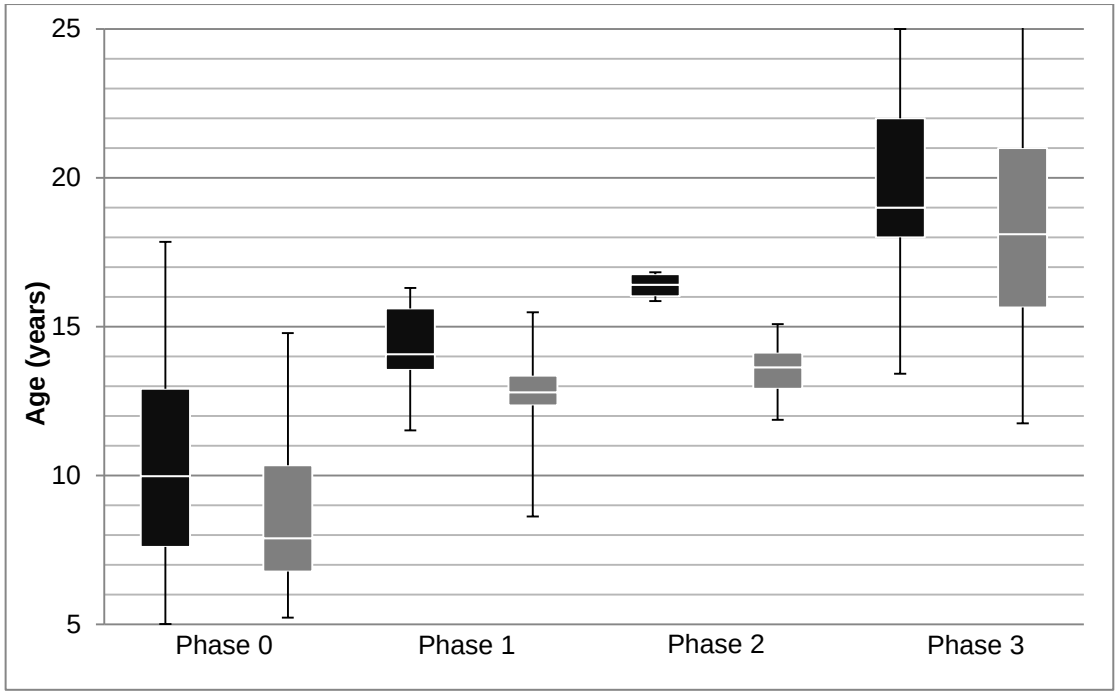

Figure 4. Distribution of the Western Australian population according to age, sex and spheno-occipital fusion stage (median and quartile range). Key: males (black); females (grey).

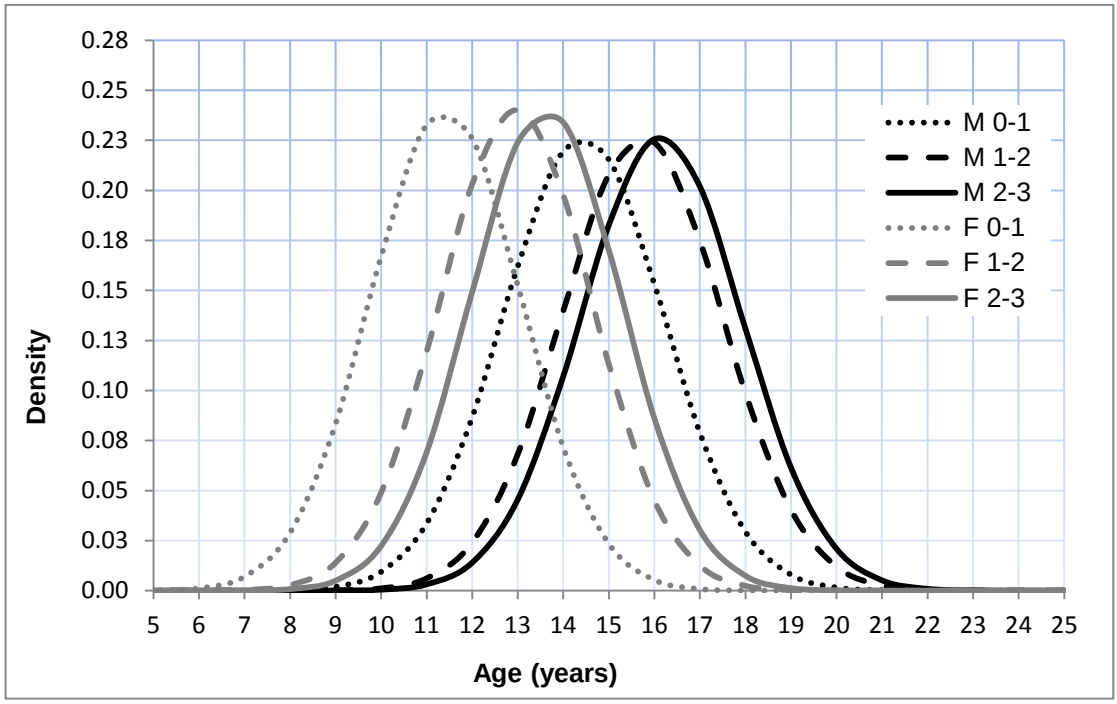

Figure 5. Probability density plot of male (black lines) and female (grey lines) age at transition distributions in the Western Australian population.

TABLES

Table 1. Definition of features used to score the spheno-occipital synchondrosis.

Stage		Description
0	Unfused	Completely open with no evidence of fusion between the basilar portion of the occipital and the sphenoid – no bone present in the gap.
1	Fusing endocranially	No more than half the length of the synchondrosis is fused – proceeding endo- to ectocranially.
2	Fusing ectocranially	Greater than half the length of the synchondrosis is fused – the ectocranial (inferior) border remains unfused.
3	Complete fusion	Completely fused with the appearance of normal bone throughout – a fusion scar may be present.

Table 2. Intra- and inter-observer agreement.

	Intra-observer		Inter-observer
	DF	AF	
No. of cases	50	50	312
Score agreement (%)	94%	94%	90%
Kappa (κ)	0.907	0.907	0.867
Significance	P <0.001	P <0.001	P <0.001

Table 3. Descriptive statistics for spheno-occipital fusion in the Western Australian population.

	n	Mean age (years)	95% CI mean age	SD	Range
Male					
Stage 0	82	10.28	9.57 - 10.99	3.30	5.01 - 17.85
Stage 1	14	14.30	13.55 - 15.06	1.44	11.52 - 16.30
Stage 2	4	16.38	15.91 - 16.85	0.48	15.86 - 16.83
Stage 3	69	19.83	19.14 - 20.53	2.94	13.42 - 25.00
Female					
Stage 0	36	8.62	7.83 - 9.40	2.40	5.23 - 14.78
Stage 1	12	12.65	11.60 - 13.71	1.86	8.63 - 15.48
Stage 2	6	13.53	12.63 - 14.44	1.13	11.88 - 15.09
Stage 3	89	18.62	17.88 - 19.36	3.55	11.75 - 25.59

Table 4. Descriptive statistics for age of transition distribution between successive spheno-occipital stages in the Western Australian population based on a log-age cumulative probit model.

Transition stages	Male		Female	
	Estimate	Std. Error	Estimate	Std. Error
0 – 1	14.44	0.298	11.42	0.374
1 – 2	15.73	0.303	12.96	0.322
2 – 3	16.16	0.308	13.62	0.313

Table 5. Age ranges for Western Australian individuals based on transition analysis probability distribution.

Fusion status	Male		Female	
	68% PI	95% PI	68% PI	95% PI
Unfused	<16.20	<17.96	<13.08	<14.74
Fusing	13.97–17.49	12.21–19.25	11.30–14.62	9.64–16.28
Fused	>14.39	>12.63	>11.95	>10.29

Key: PI = prediction interval; unfused = stage 0; fusing = stages 1-2; fused = stage 3.