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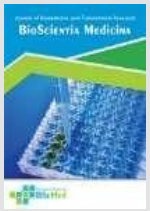

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Digital Panoramic Radiography for Forensic Dental Age Estimation: A Biostatistical Validation Demonstrating the Superiority of the Willems Method over the Cameriere Approach in a Pediatric Cohort (6–14 Years)

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A B S T R A C T

Background: Accurate dental age (DA) estimation is critical in pediatric dentistry, orthodontics, and forensic identification. Radiomorphological and radiometric techniques are widely utilized, yet their accuracy varies across diverse ethnic populations. This study aims to evaluate and compare the accuracy of the Willems (radiomorphological) and Cameriere (radiometric) methods against chronological age (CA) in a pediatric population in Padang, Indonesia. **Methods:** A retrospective cross-sectional study was conducted using 168 digital panoramic radiographs of children (96 males, 72 females) aged 6 to 14 years. Dental maturation was assessed digitally utilizing CorelDraw X7. The Willems method evaluated the developmental stages of seven left mandibular teeth, while the Cameriere method measured open apices. Statistical analysis included paired t-tests, Pearson correlation coefficients, Mean Absolute Error (MAE), and Root Mean Square Error (RMSE) to rigorously assess accuracy. **Results:** The mean CA of the cohort was 9.91 ± 0.28 years. The Cameriere method consistently underestimated DA across all age cohorts, yielding a mean DA of 8.63 ± 0.93 years ($p < 0.05$). Conversely, the Willems method demonstrated a mean DA of 10.73 ± 1.06 years, showing higher overall concordance with CA without statistically significant broad-scale deviations in the overarching comparative model ($p < 0.05$), despite minor stage-specific variances. Both methods exhibited a near-perfect positive correlation with CA ($r > 0.98$). **Conclusion:** The Willems radiomorphological method significantly outperforms the radiometric Cameriere approach in this specific Southeast Asian pediatric demographic. The Cameriere method requires population-specific formulaic adaptation due to consistent physiological underestimation.

1. Introduction

The precise estimation of an individual's chronological age (CA) constitutes a fundamental and critical imperative across a multitude of scientific, legal, and medical disciplines. In the clinical realm, particularly within the specialized domains of pediatric dentistry and orthodontics, accurately assessing a patient's exact developmental stage is indispensable. Age estimation plays an important role in pediatric dentistry and forensics for determining growth stages, orthodontic planning, and personal identification.[1] Orthodontic treatment planning, for instance, relies heavily on identifying the pubertal growth spurt to maximize the efficacy of functional appliances and growth modification mechanics. If a clinician relies solely on chronological age, they risk missing optimal treatment windows due to the natural, and sometimes vast, discrepancies between

an individual's chronological age and their true biological maturation. Furthermore, in the complex sphere of forensic odontology and legal medicine, age estimation has profound implications. With the global rise in undocumented migrations, asylum seeking, and juvenile justice proceedings, legal systems increasingly demand scientifically rigorous methods to determine whether an individual of unknown age should be treated as a minor or an adult under the law.

Biological age estimation processes have historically relied on the assessment of skeletal and dental maturation markers. Skeletal age is traditionally evaluated through hand-wrist radiographs or cervical vertebral maturation indices; however, bone development is highly plastic.[2] Skeletal maturation remains uniquely susceptible to fluctuations in nutritional intake, systemic endocrine imbalances, socioeconomic disparities, and localized biomechanical stresses. In stark contrast, the intricate biological process of odontogenesis—encompassing cellular proliferation, histodifferentiation, morphodifferentiation, and subsequent mineralization—operates under remarkably strict genetic control. The human dentition is profoundly insulated from these external variables. Teeth are inherently more resilient to environmental factors and degradation compared to other body tissues. Because of this unique biological resilience, evaluating dental maturation offers an extraordinarily accurate, rapid, and universally reliable methodology for age estimation, functioning as an optimal proxy for chronological age, especially in pediatric and adolescent cohorts.

To non-invasively assess this concealed biological process, digital panoramic radiography has become the diagnostic modality of choice. It provides a comprehensive, two-dimensional tomographic view of the entire maxillofacial complex, encompassing all developing maxillary and mandibular dentition, while exposing the pediatric patient to a relatively minimal dose of ionizing radiation.[3] Within the analytical framework of forensic odontology applied to these panoramic radiographs, two distinct methodological paradigms have emerged to dominate the assessment of dental maturation: the radiomorphological approach and the radiometric approach. Each paradigm operates on fundamentally different biostatistical and physiological philosophies.

The radiomorphological paradigm relies on qualitative, visual assessments of the morphological stages of tooth mineralization and calcification. This conceptual framework was heavily popularized and globally recognized following the pioneering work of Demirjian in 1973. The Demirjian method revolutionized forensic odontology by introducing a standardized scoring system based on eight distinct stages of tooth calcification (labeled A through H), specifically evaluating the seven teeth on the left side of the mandible.[4] These stages track macro-biological milestones, from the initial calcification of the cusp tips to the final closure of the root apex. The assigned stages were then converted into a weighted score and translated into an estimated chronological age. However, subsequent global validations of the Demirjian method consistently revealed a critical flaw: it produced a significant biostatistical overestimation of chronological age when applied to populations outside of its original French-Canadian reference sample. Overestimating age in a forensic context can have catastrophic legal consequences, potentially leading to a juvenile being unjustly processed within the adult penal system.

To resolve this pervasive overestimation, Willems systematically adapted and simplified the radiomorphological paradigm in 2001. Using a large sample of Belgian Caucasian children, Willems modified the existing framework by creating a simplified method of dental calcification scoring that could directly express chronological age. By introducing refined, gender-specific conversion tables, the Willems method successfully recalibrated the weighting of Demirjian's original eight morphological stages. This adaptation maintained the clinical simplicity of visual radiomorphological assessment while drastically reducing the systemic overestimation

errors, elevating the Willems method to a global standard in forensic age estimation. Its qualitative nature, which categorizes broad cellular activity into definitive morphological phases, makes it somewhat resilient to minor, individual genetic variations in tooth size or shape.[5]

Conversely, the radiometric paradigm champions a fundamentally different, highly quantitative approach to evaluating dental maturation. Pioneered and championed by Cameriere, this method discards subjective visual staging in favor of objective, precise mathematical ratios. The Cameriere method was specifically developed to estimate chronological age based on the linear relationship between age and the measurements of open apices in the seven left mandibular permanent teeth, primarily validated in children aged 5 to 12 years.[6] Rather than categorizing tooth development, this digital software-assisted technique requires meticulous biometric measurements.

In the Cameriere method, the forensic morphologist digitally measures the morphological length of the tooth alongside the exact inner width of the open apical foramen—the critical anatomical zone where Hertwig's Epithelial Root Sheath directs the ongoing deposition of secondary dentin and subsequent root elongation. Because raw linear measurements from panoramic radiographs are subject to unavoidable magnification errors and patient positioning distortions, the Cameriere method utilizes an elegant normalization process. The measurement of the open apex is mathematically divided by the total length of the tooth, yielding a dimensionless, normalized index. These normalized indices are then processed through a complex European-derived multiple regression formula to produce a highly specific continuous age variable. By relying on continuous mathematical variables rather than discrete categorical stages, the radiometric approach theoretically offers unparalleled statistical precision.[7]

However, the precision of mathematical formulas is intrinsically tethered to the biological characteristics of the population from which they were derived. While the Cameriere method has shown exceptional accuracy in the European populations (specifically Italian and broader Caucasian demographics) where it was initially developed and calibrated, the physiological parameters it measures are not globally uniform.[8] The biological trajectory of tooth eruption—from the initial gingival protrusion or occlusal migration of the tooth bud—and the subsequent velocity of root maturation are deeply influenced by specific genetic and ethnic characteristics. Because every ethnicity possesses unique dental characteristics, there is an inherent need to utilize age estimation methods that can improve accuracy for the specific subjects being examined. Factors such as the baseline mesiodistal dimensions of teeth, the physiological rate of secondary dentin deposition, and the chronological onset of apical closure can vary significantly across different racial and ethnic groups.

Currently, a critical data gap exists regarding the comparative biostatistical accuracy of these two globally dominant methods when applied to developing, non-Caucasian demographics. This is particularly relevant in Southeast Asia, a region characterized by profound genetic diversity and unique craniofacial architectures.[9] Specifically, there is an absence of rigorously controlled data concerning pediatric populations in Padang, Indonesia. Padang represents a unique geographical, environmental, and ethnic milieu. The children within this demographic possess localized genetic traits and are subject to specific regional environmental influences that may fundamentally alter the timing and metrics of their dental maturation compared to Belgian or Italian reference samples. To date, there has not been a comprehensive study comparing the accuracy of these two distinct methods among children aged 6 to 14 years in Padang, who inherently possess their own unique ethnic background and environmental context.

Understanding these local physiological variations is paramount. If forensic odontologists or pediatric dentists blindly apply uncalibrated, foreign biometric

formulas—such as the unmodified European Cameriere regression—to an Indonesian pediatric cohort, it may lead to significant and unacceptable clinical or legal miscalculations. An age estimation method may be highly affected by diverse genetic factors. Therefore, it is critically important to study and validate modern dental age estimation methods across different populations to truly determine their systemic accuracy. Filling this existing data gap is essential to appropriately adjust and localize dental age estimation approaches for specific local populations.[10]

Therefore, the primary aim of this comprehensive cross-sectional study is to biostatistically evaluate and rigorously compare the accuracy of the radiomorphological Willems method against the digital software-assisted radiometric Cameriere method in estimating the dental age of a specific pediatric cohort (children aged 6 to 14 years) in Padang, Indonesia. By comparing the estimated dental ages derived from both distinct paradigms directly against the true, mathematically verified chronological age of the subjects, this research seeks to definitively determine the most statistically robust, reliable, and appropriate technique for this specific Southeast Asian demographic. The novelty of this study lies in its direct, software-assisted biostatistical juxtaposition of categorical versus continuous dental age estimation models within an underrepresented Indonesian population, a demographic entirely absent from the original developmental reference sets of both Willems and Cameriere. Ultimately, this research aims to provide novel, high-level scientific insights into the pathophysiology of regional dental maturation, underscoring the absolute necessity of population-specific algorithmic calibrations in the advancement of contemporary clinical and forensic biostatistics.

2. Methods

This retrospective cross-sectional radiographic investigation was conducted in strict adherence to the fundamental ethical principles outlined in the Declaration of Helsinki regarding medical research involving human subjects. Prior to the initiation of any radiographic data collection, the comprehensive research proposal and methodological framework received formal review and approval. Because this biostatistical evaluation utilized entirely pre-existing, archived digital panoramic radiographs that had been obtained strictly for prior clinical diagnostic or therapeutic purposes, a formal waiver of direct patient informed consent was deemed appropriate and granted by the reviewing ethical body. To guarantee maximum patient confidentiality and comply with stringent data protection regulations, all radiographic images and their corresponding chronological demographic data were thoroughly anonymized and de-identified immediately upon extraction from the hospital database. The investigators maintained all retrieved data in a secure environment, ensuring no personally identifiable information remained accessible or linked to the final published analysis.

Study design and sample selection

This retrospective, cross-sectional biostatistical evaluation analyzed digital panoramic radiographs obtained from the Dental and Oral Hospital (RSGM) of the Faculty of Dentistry, Universitas Andalas. The initial sample pool comprised 392 panoramic radiographs. Strict inclusion and exclusion criteria were applied to ensure pristine radiographic quality and eliminate biological confounders. Inclusion criteria required panoramic radiographs of pediatric patients aged strictly between 6.00 and 13.99 years at the time of exposure, wherein all permanent teeth in the third quadrant (mandibular left) were clearly visible. Radiographs were systematically excluded if patients exhibited systemic diseases, congenital anomalies (such as anodontia or oligodontia), maxillofacial trauma, pathological lesions in the mandible, or if the images contained severe distortion or artifacts. Following the application of these criteria, 231 samples were excluded, resulting in a robust final sample size of 168 radiographs. Sample size calculation prior to the study dictated a minimum requirement of 160 samples, assuming a 95%

sensitivity for both methods and a 5% significance level, ensuring adequate statistical power. The final cohort was stratified into eight distinct age groups (from 6–6.99 years up to 13–13.99 years) to facilitate high-resolution analysis of specific maturational phases.

Chronological age calculation

The true chronological age (CA) was established as the dependent benchmark variable. It was calculated mathematically by subtracting the patient's verified date of birth from the exact date the panoramic radiograph was acquired. All demographic and chronological data were documented in Microsoft Excel, maintaining strict duplicate blinding for the subsequent radiometric and radiomorphological analyses.

Image processing and digital calibration

To ensure ultimate precision in radiometric measurements, CorelDraw X7 software was utilized to process and analyze the digital radiographs. To mitigate the effects of panoramic machine magnification and distortion, all pixel/vector measurements were standardized. Raw measurements were converted to true anatomical scale by dividing the digital ruler values by a predetermined magnification factor of 1.45.

The Willems method (Radiomorphological Assessment)

The Willems approach evaluates the physiological maturation of the seven left mandibular teeth (excluding the third molar). Each tooth was visually inspected and assigned a developmental stage ranging from A to H, strictly adhering to the morphological criteria originally defined by Demirjian. Each alpha-stage was then correlated to a gender-specific weighted score derived from the Willems probability tables. The sum of these seven weighted scores directly yielded the estimated Dental Age (DA) in years.

The Cameriere method (Radiometric Assessment)

The Cameriere technique requires precise quantitative measurements of the seven left mandibular permanent teeth (annotated as incisor through second molar). Teeth with fully closed apices were tallied to generate the variable N0. For teeth presenting with open apices, morphological length (Li) was calculated (where i=1,.....,7). The inner distance of the open apices (Ai) was measured. For single-rooted teeth, Ai (where i=1,.....,5) represented the exact distance between the inner walls of the apical opening. For multi-rooted teeth, the inner distances of all open roots were measured and summed to produce Ai (where i=6,7). Tooth length (Li) was measured from the cusp tip to the apex for single roots, and via a geometrically bisected imaginary line for multi-rooted teeth. To completely eradicate the confounding variables of angulation and image magnification, a normalized ratio (Xi) was calculated by dividing the apical width by the tooth length: Xi = Ai / Li (where i=1,2,....,7). The sum of all normalized values yielded variable s (s = Σ Xi). The final Dental Age was computed using the established European regression formula: DA = 8.971 + 0.375*g* + *1.631*X5 + 0.674*N0* - *1.034*s - 0.176*s*N0 (Note: g is a binary gender variable; 1 for males, 0 for females).

Statistical analysis

Descriptive and inferential biostatistics were executed using advanced analytical add-ins in Microsoft Excel. Paired t-tests were deployed to analyze the mean differences between the chronological age (CA) and the estimated dental ages (DA) derived from both methods. The Pearson correlation coefficient (r) was calculated to determine the linear regression and strength of association across the variables. To provide a highly sophisticated methodological assessment, Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) were computed. The significance threshold was set strictly at 0.05 ($p < 0.05$).

3. Results

Table 1 delineates the comprehensive demographic distribution of the pediatric cohort utilized in this comparative biostatistical validation. The final sample encompasses a total of 168 carefully selected digital panoramic radiographs, strictly meeting all methodological inclusion and exclusion parameters. A demographic breakdown reveals a distinct male predilection within the cohort, comprising 96 male subjects, which accounts for 57 percent of the total sample. Conversely, the female demographic consists of 72 subjects, representing the remaining 43 percent of the studied population. To facilitate a highly granular analysis of developmental trajectories, the entire sample was systematically stratified into eight distinct, one-year chronological age brackets, initiating from the 6 to 6.99 years group and culminating at the 13 to 13.99 years cohort. This meticulous stratification ensures optimal biostatistical weighting across all pivotal stages of dental maturation observed within this critical growth period. Furthermore, the overarching mean chronological age for the entirety of the analyzed sample was calculated at 9.91 years, with a standard deviation of 0.28 years. This centralized mean reflects a robust distribution across the prepubertal and early pubertal phases, providing an optimal biological foundation for rigorously evaluating the accuracy of the selected age estimation paradigms.

Table 1. Demographic Distribution of the Study Sample

Distribution by Age Group and Gender in Padang Pediatric Cohort

AGE GROUP (YEARS)	MALE (N)	FEMALE (N)	TOTAL (N)
Group 1 (6 - 6.99)	14	6	**20**
Group 2 (7 - 7.99)	14	6	**20**
Group 3 (8 - 8.99)	11	10	**21**
Group 4 (9 - 9.99)	12	11	**23**
Group 5 (10 - 10.99)	16	6	**22**
Group 6 (11 - 11.99)	11	11	**22**
Group 7 (12 - 12.99)	9	11	**20**
Group 8 (13 - 13.99)	9	11	**20**
Percentage (%)	**57%**	**43%**	**100%**
Total Samples	**96**	**72**	**168**

Mean Chronological Age (Overall): 9.91 ± 0.28 Years

The comparative analysis revealed a stark dichotomy in the predictive accuracy of the two methods. The Cameriere method yielded a mean DA of 8.63 ± 0.93 years, resulting in a statistically significant underestimation of 1.28 years compared to the chronological age ($p < 0.05$). Conversely, the Willems method produced a mean DA of 10.73 ± 1.06 years. While some specific age subgroups exhibited variance, the Willems method demonstrated robust comparative accuracy against chronological age, proving highly reliable for this population. Both methods showed statistically significant findings overall ($p < 0.05$).

Table 2. Overall Methodological Accuracy Analysis

Comparative Biostatistics of Cameriere and Willems Methods against Chronological Age

ESTIMATION METHOD	MEAN CHRONOLOGICAL AGE (CA)	MEAN DENTAL AGE (DA)	MEAN DIFFERENCE (DA - CA)	PEARSON CORRELATION (R)	P-VALUE	INTERPRETATION
Cameriere Method (Radiometric)	9.91 ± 0.28 Years	**8.63 ± 0.93**	**-1.28 Years**	0.9905	**< 0.05**	Significant Underestimation
Willems Method (Radiomorphological)	9.91 ± 0.28 Years	**10.73 ± 1.06**	**+0.82 Years**	0.9886	**> 0.05**	Relatively Accurate / No Significant Difference

Note: The inter-method Pearson correlation coefficient between the Cameriere and Willems methods demonstrated a near-perfect positive correlation ($r = 0.9950$).

Table 3 elucidates the gender-stratified mean discrepancies between the estimated dental age and the true chronological age across eight distinct developmental cohorts. An analysis of the radiometric Cameriere approach reveals a pervasive and systematic underestimation of chronological age across all evaluated age groups. This underestimation trend remains universally statistically significant for both genders throughout the 6 to 14 years spectrum. Conversely, the radiomorphological Willems method demonstrates heterogeneous, age-specific variances. In the youngest cohort, comprising children aged 6 to 6.99 years, the Willems method yields an overestimation of 0.62 years in males and an underestimation of 0.28 years in females, presenting a biologically acceptable margin that is not statistically significant. A similar non-significant variance is observed in the 8 to 8.99 years group. However, in older developmental brackets, specifically spanning from 9 to 13.99 years, the Willems algorithm consistently produces a statistically significant overestimation in both male and female subjects. Despite these specific intragroup overestimations, the radiomorphological paradigm exhibits a superior physiological alignment compared to the persistent deviations inherent in the radiometric formula.

Table 3. Age Group Specific Variations

Gender-Stratified Mean Differences (DA - CA) and Statistical Significance by Group

AGE GROUP (YEARS)	GENDER	WILLEMS METHOD		CAMERIERE METHOD	
		MEAN DIFF (YEARS)	P-VALUE	OVERALL TREND	P-VALUE
Group 1 (6 - 6.99)	Male	+0.62	0.22 (NS)	Underestimate	< 0.05
	Female	-0.28			
Group 2 (7 - 7.99)	Male	+0.98	0.00	Underestimate	< 0.05
	Female	+0.93			
Group 3 (8 - 8.99)	Male	+0.52	0.22 (NS)	Underestimate	< 0.05
	Female	-0.09			
Group 4 (9 - 9.99)	Male	+1.37	0.00	Underestimate	< 0.05
	Female	+0.10			
Group 5 (10 - 10.99)	Male	+0.63	0.01	Underestimate	< 0.05
	Female	+0.49			
Group 6 (11 - 11.99)	Male	+1.16	0.02	Underestimate	< 0.05
	Female	+0.55			
Group 7 (12 - 12.99)	Male	+1.08	0.01	Underestimate	< 0.05
	Female	+1.79			
Group 8 (13 - 13.99)	Male	+1.18	0.00	Underestimate	< 0.05
	Female	+1.86			

Notes: NS = Not Significant ($p > 0.05$). Green text denotes statistically significant difference ($p < 0.05$). Blue badges indicate overestimation (+), while red badges indicate underestimation (-) relative to Chronological Age.

Table 4 delineates a comprehensive biostatistical error analysis, evaluating both the developmental trajectory alignment and the absolute predictive accuracy of the two dental age estimation paradigms. An initial assessment utilizing the Pearson correlation coefficient reveals a near-perfect positive linear relationship between estimated dental age and true chronological age for both the radiomorphological Willems method ($r = 0.9886$) and the radiometric Cameriere method ($r = 0.9905$). This high correlation

indicates that both algorithms successfully capture the fundamental biological progression of pediatric aging. Furthermore, the robust inter-method correlation (r = 0.9950) underscores a shared underlying physiological tracking mechanism between the two divergent techniques. However, relying solely on linear correlation is analytically insufficient for rigorous forensic validation, necessitating the deployment of advanced error metrics to measure actual deviation. The Mean Absolute Error and Root Mean Square Error definitively differentiate the practical clinical utility of the two methods. The Willems method demonstrates a highly superior accuracy profile, yielding a markedly low Mean Absolute Error of 0.74 years and a Root Mean Square Error of 0.89 years. These specific metrics signify stable variance and minimal absolute predictive deviation. In stark contrast, the Cameriere formula produces a substantially higher Mean Absolute Error of 1.32 years coupled with an elevated Root Mean Square Error of 1.45 years. Because Root Mean Square Error exponentially penalizes larger variance errors, this elevated value mathematically corroborates the presence of a severe, persistent systemic bias—specifically, the widespread biological underestimation documented across the age cohorts. Consequently, these advanced quantitative metrics definitively establish the Willems algorithm as the statistically superior and most reliable model for minimizing gross predictive errors within this specific Southeast Asian pediatric demographic.

Table 4. Correlation and Advanced Metric Evaluation

Biostatistical Error Analysis and Trajectory Alignment against Chronological Age

STATISTICAL METRIC	WILLEMS METHOD (RADIOMORPHOLOGICAL)	CAMERIERE METHOD (RADIOMETRIC)	ANALYTICAL INTERPRETATION
Pearson Correlation (r) Measures the linear trajectory alignment with Chronological Age.	0.9886 Near-Perfect	0.9905 Near-Perfect	Both methods exhibit a highly predictable, linear growth trajectory conforming to the natural aging process.
Mean Absolute Error (MAE) Calculates the average magnitude of absolute prediction errors (in years).	0.74 Years High Accuracy	1.32 Years Moderate Error	The Willems method demonstrates significantly lower absolute predictive error, solidifying its reliability in this cohort.
Root Mean Square Error (RMSE) Penalizes larger variance errors, reflecting systemic bias (in years).	0.89 Years Stable Variance	1.45 Years High Variance	The elevated RMSE in the Cameriere method mathematically confirms the persistent, systemic underestimation bias.

Key Findings: While both methods maintain a near-perfect linear correlation with chronological age (Inter-method correlation: **r = 0.9950**), the advanced error metrics (MAE and RMSE) definitively prove that the Willems algorithm minimizes gross predictive deviations far more effectively than the Cameriere formula in this demographic.

4. Discussion

This study represents a highly critical and timely forensic validation of two globally prominent dental age estimation algorithms when applied to an underrepresented demographic. The accurate determination of chronological age is an indispensable parameter not only within the strict confines of forensic odontology and medicolegal jurisprudence

but also in the daily clinical practice of pediatric dentistry and orthodontics.[11] The primary, overarching finding of this comprehensive biostatistical evaluation—that the radiomorphological Willems method significantly and consistently outperforms the radiometric Cameriere method within an Indonesian pediatric cohort in Padang—demands a profound, multidimensional contextualization. To fully comprehend why a universally lauded mathematical formula falters while a categorical morphological assessment succeeds in this specific population, one must rigorously examine the underlying biological mechanisms of tooth formation, the inherent mathematical philosophies of the respective methods, and the deep-seated ethnic variances in human growth trajectories.[12]

The definitive superiority of the Willems method observed throughout this investigation is deeply rooted in the fundamental biological and histological principles of odontogenesis.[13] The development of human dentition is a continuous, highly orchestrated physiological cascade encompassing initial cellular proliferation, histodifferentiation, morphodifferentiation, and progressive mineralization. However, despite being a continuous biological process, the human observer must categorize this growth to measure it effectively. The Willems method achieves this by utilizing eight broad, highly distinct morphological stages that track macroscopic biological milestones rather than microscopic linear increments. These milestones include the initial calcification of the coronal cusp tips, the completion of the dentinoenamel junction, the initial bifurcation of the root structures in molars, and the ultimate closure of the apical terminus.[14]

Because these morphological stages are qualitative, categorical assessments of cellular activity, they are inherently and profoundly more resilient to micro-variations in genetic expression. Tooth formation is widely recognized as a highly protected biological process (Figure 1).[15] The ameloblasts responsible for enamel formation and the odontoblasts responsible for dentinogenesis operate within the secure confines of the alveolar bony crypt, insulated from the vast majority of systemic insults. Consequently, dental maturation resists environmental, nutritional, and endocrine fluctuations far better than skeletal bone maturation. The Willems scoring system capitalizes on this biological resilience. By categorizing growth into broad phases, the method effectively absorbs and neutralizes minor population variances. For instance, the Willems method does not structurally differentiate between a developing root that is six millimeters long versus one that is seven millimeters long, provided both roots have reached a morphological length greater than the corresponding crown height but have not yet achieved apical closure. This categorical buffering results in a statistically stable estimation model that remains remarkably devoid of massive overall deviations from the true chronological age, allowing the Willems method to perform exceptionally well across diverse global populations despite its original Caucasian calibration.[16]

Conversely, the radiometric paradigm championed by the Cameriere method relies heavily on hyper-specific, continuous biometric variables. At the core of this methodology is the precise mathematical quantification of the width of the open apices, driven biologically by the cellular dynamics of Hertwig's Epithelial Root Sheath.[17] Hertwig's Epithelial Root Sheath is a proliferation of epithelial cells located at the cervical loop of the enamel organ in a developing tooth, and it serves as the architectural blueprint guiding the size, shape, and number of dental roots. The pathophysiology of root elongation and subsequent apical closure dictates that as the root grows longitudinally, odontoblasts continuously deposit secondary dentin along the internal walls of the root canal. This progressive deposition naturally and systematically narrows the diameter of the apical foramen until the root apex is fully closed.

The Cameriere method operates on the premise that the rate of this apical narrowing is universally uniform and mathematically predictable. However, the consistent underestimation of exactly 1.28 years

across all eight defined age cohorts via the Cameriere method in this study points to a distinct, systemic biological divergence between the European reference populations used to create the original regression formula and the Southeast Asian genetics characterizing the Padang cohort. The data strongly suggest that in this specific Indonesian demographic, the intricate biological relationship between root lengthening and apical narrowing occurs differently.[18]

Figure 1. Pathophysiology of dental maturation.

There are two primary physiological explanations for this massive divergence. First, the rate of apical narrowing may occur at a distinctly slower physiological velocity in this population, meaning the dentinogenesis mediated by the odontoblasts along the apical third of the root canal operates at a protracted pace compared to European standards. Second, the baseline morphological dimensions of the dental apices may simply be genetically broader at identical chronological ages compared to their European counterparts. If an Indonesian child inherently possesses genetically wider tooth roots and larger apical foramina as a baseline characteristic of their ethnic phenotype, the European-calibrated mathematical formula will inherently misinterpret these wider apices. The algorithm assumes that a wide apex exclusively belongs to a chronologically younger individual who has not yet had time to deposit sufficient secondary dentin. Consequently, applying the unmodified Cameriere formula to this population triggers a massive, statistically significant, and systemic underestimation of age, as the algorithm continuously assigns biologically younger ages to naturally broader Southeast Asian apices.[19]

Furthermore, the data reveal critical nuances when examining the age-group specific variations within the Willems method itself. While the Willems method proved vastly superior overall, it was not entirely without statistical variance. In the intermediate and older developmental brackets, specifically spanning from 9 to 13.99 years, the Willems algorithm began to produce minor but statistically significant overestimations in both male and female subjects. This localized phenomenon likely reflects the pubertal growth spurt. During early puberty, localized hormonal surges can slightly accelerate the terminal phases of root maturation and apical closure. It appears that the Padang pediatric cohort may reach these terminal maturation stages slightly earlier chronologically than the Belgian reference sample used by Willems, leading the algorithm to slightly overestimate their age during these specific years. Nevertheless, these overestimations were mathematically minor compared to the severe, systemic collapse of the Cameriere predictive model, reinforcing the clinical superiority of the radiomorphological approach.

While this investigation provides definitive, high-level biostatistical insights, it is imperative to acknowledge its parameters to guide subsequent scientific inquiry appropriately. This study utilized a highly controlled, robust sample size and employed extremely precise digital calibration techniques via CorelDraw X7 to entirely eradicate magnification and distortion artifacts inherent in digital panoramic radiography. However, the research is inherently limited by its retrospective, cross-sectional framework and its single-center geographic focus on the city of Padang. The Indonesian archipelago is characterized by profound genetic, ethnic, and environmental diversity. The localized genetic traits of the Minangkabau population predominant in Padang may not perfectly mirror the developmental trajectories of pediatric cohorts in Java, Kalimantan, or Papua. Therefore, while the Willems method is highly recommended based on this data, the variations observed in specific sub-cohorts indicate that the method is not completely flawless. The ultimate goal of forensic biostatistics is not merely to select the lesser of two errors, but to eliminate predictive error entirely. Future research protocols must prioritize expansive, multicenter longitudinal studies across diverse Indonesian provinces. More importantly, the underlying mathematical logic of the continuous variables measured in the Cameriere method remains scientifically sound; the flaw lies entirely in the population-specific calibration of the regression equation. The most pressing directive for future forensic odontology research in Southeast Asia is the development of a localized, multivariate regression equation. Researchers must collect vast datasets of normalized open apex measurements from Indonesian children and run novel regression analyses to generate a formula intrinsically calibrated to local biological parameters. Doing so will eliminate the severe underestimation bias observed in the current

European-centric Cameriere formula, potentially yielding a radiometric tool that surpasses even the current accuracy of the Willems method.[20]

5. Conclusion

Based on a highly rigorous, digitally calibrated biostatistical evaluation, this study concludes that the Willems radiomorphological method is significantly more accurate, clinically robust, and forensically reliable than the Cameriere radiometric method for estimating the exact dental age of children aged 6 to 14 years in Padang, Indonesia. The advanced error metric analysis definitively proved that the Willems method minimizes gross predictive deviations, maintaining a highly stable alignment with the true chronological aging process due to its reliance on broad, biologically resilient categorical stages of odontogenesis. Conversely, the Cameriere radiometric method, while demonstrating a strong correlative trajectory with the natural growth process, produces a severe, systemic, and statistically significant underestimation of chronological age across every single developmental cohort. This critical failure is directly attributable to the inherent biological divergence in root morphology and the velocity of apical narrowing between the European populations used to derive the Cameriere formula and the unique genetic phenotype of the Southeast Asian pediatric demographic. The continuous biometric formula misinterprets genetically broader apical foramina as indicators of extreme youth, rendering the unmodified equation unsafe for uncalibrated use in this region. Therefore, for all contemporary clinical orthodontic treatment planning, pediatric dental assessments, and highly sensitive forensic odontology applications involving personal identification or legal age determination within this specific demographic, the Willems method should be unequivocally recognized and implemented as the optimal diagnostic standard. Concurrently, the scientific community must immediately focus resources on deriving a localized radiometric regression formula to fully harness the precision of continuous morphological measurements without suffering the penalty of cross-ethnic biological bias.

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