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ORIGINAL ARTICLE

Forensic Age Estimation Using Coronal Pulp Cavity Index (CPCI) in Mandibular Second Premolars and First Molars: A Radiographic Study in Sub-Population of Peshawar

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ABSTRACT

Background: This study aimed to determine the accuracy of age estimation using the Coronal Pulp Cavity Index (CPCI) measured on orthopantomograms (OPGs) of mandibular second premolars and first molars in a Pakistani adult population.
Methodology: A total of 120 orthopantomograms of individuals aged 15 to 75 years were analyzed on IC Measure software from the archives of Khyber College of Dentistry and Rehman College of Dentistry Peshawar. Coronal Height (CH) and Coronal Pulp Cavity Height (CPCH) of mandibular premolars and molars were measured to calculate CPCI. Intra-rater reliability was assessed using intraclass correlation coefficient (ICC). Associations with chronological age were examined using Pearson correlations while simple and multiple linear regression models were built to estimate chronological age.
Results: All the OPG parameters demonstrated strong negative correlation with chronological age with molar CPCH showing the most negative trend ($r=-0.859$, $p<0.001$). The univariate regression model predicted age with a standard Error of Estimate (SEE) exceeding ± 8 years, indicating limited standalone accuracy. Mandibular molars yielded a greater predictive accuracy than premolars. With multivariate approach, a substantial improvement in precision was observed achieving an SEE of ±4.8 years and a Mean Absolute Error (MAE) of ± 3 years.
Conclusion: CPCI provides a reliable, non-invasive tool for forensic age estimation in the Pakistani population, especially when multiple parameters are incorporated. Hence, population- and tooth-specific regression models are recommended to improve forensic precision in age estimation.
Keywords: Forensic dentistry, Coronal Pulp Cavity Index, Age estimation, Orthopantomogram, IC Measure software

INTRODUCTION: In forensic dentistry, various methods are used to help in the identification of human remains [1]. These methods are employed to reconstruct personal profiles using dental evidence [2]. Dental indices however, have become essential tools in forensic investigations when other identification methods are not feasible [3]. By combining these tools with other forensic odontology techniques, investigators can enhance the accuracy of personal identification, which is essential in solving criminal cases and identifying remains in mass disasters [4].

Traditional dental age estimation methods relied on invasive techniques (e.g., tooth extraction for histological examination as in Gustafson's method) hence, radiographic methods have gained prominence for being non-invasive [5,6] Moreover biochemical approaches like aspartic acid racemization provide additional age markers but are technique sensitive and expensive [7].

Radiological methods are recently being used to assess tooth development and pulp size changes [8]. Kvaal and Solheim in 1994 proposed a combined radiological and morphological age estimation method that still required tooth extraction [9]. To overcome this limitation, Kvaal et al. in 1995 introduced a purely radiological approach using measurements of tooth and pulp length and width ratios on IOPA radiographs, enabling non-invasive dental age estimation [10]. Later Bosman et al. (2005) applied Kvaal's method using orthopantomograms (OPG) and found it provided a high predictive value for age determination [11]. In 1985, Ikeda et al. developed the Coronal Pulp Cavity Index (CPCI) as later described by Drushini, which calculated the ratio of coronal pulp cavity height to crown height from dental radiographs to estimate age [12].

Overall, CPCI and Kvaal's methods stand out for being noninvasive, cost-effective, and reasonably accurate tools for forensic age estimation having an advantage of correlating well with chronological age [13]. The radiological non-invasive dental age estimation methods used either cone-beam computed tomography (CBCT)-based or orthopantomograms (OPGs) for analyses. In this study OPGs were used for measurements. CBCT provides three-dimensional assessment of pulp volume and generally demonstrates higher accuracy than two-dimensional radiographs [14]. However, its routine forensic application is limited by higher radiation exposure, increased cost, and limited availability in many low- and middle-income countries [15]. In contrast, orthopantomograms (OPGs) are widely available, inexpensive, and routinely acquired in dental practice, making them attractive for large-scale forensic investigations [16]. Nevertheless, OPGs are susceptible to magnification, distortion, and positioning errors, which may influence measurement accuracy [17].

There is limited population-specific data on the Coronal Pulp Cavity Index (CPCI) in Pakistani and Asian groups, restricting its forensic applicability in these regions.[18] Existing studies often show weak correlation between CPCI and chronological age, highlighting the need for localized validation.[14] Additionally, tooth-specific regression models are lacking, despite variations in pulp cavity changes among different teeth. Further, inconsistent imaging protocols reduce comparability across studies, underscoring the need for standardized methodologies.

The objective of this study was to evaluate how well the Coronal Pulp Cavity Index (CPCI) correlates with chronological age using mandibular second premolars and first molars on OPGs in a Pakistani cohort. We aim to develop a tooth-specific regression model for age estimation and to assess its accuracy in this population. With this approach the effectiveness of CPCI as a reliable, noninvasive tool for forensic age estimation and the quantification of its predictive power through statistical modeling will be established. These findings will not only create but also validate a prediction model that assesses how accurately this method estimates age. The strengths and limitations of CPCI aim to provide a deeper understanding of how this tool can be effectively integrated into forensic investigations.

METHODS: The study commenced after approval from the Khyber Medical University (KMU) Institutional Research Ethical Board (KMU/IBMS/IRBE/9thmeeting/2024/1753) dated 16th April 2024 and ethical committees of Khyber College of Dentistry (182/ADR/KCD) dated 2nd September 2024 and Rehman College of Dentistry (RMI/RMI-REC/Approval/215) dated 12th June 2024. A cross-sectional observational study was conducted using archived digital orthopantomograms (OPGs) of patients presenting to the departments of Oral and Maxillofacial Surgery and Orthodontics at both institutions between August 2024 and January 2025.

A total of 120 OPGs were selected through non-probability purposive sampling according to predefined inclusion criteria to ensure optimal radiographic quality and reliable morphometric measurements. Healthy mandibular second premolars and first molars were analyzed because they show clear coronal landmarks on panoramic radiographs, and have been widely used in previous CPCI studies. Their larger crown and pulp chamber dimensions also improve measurement accuracy and reproducibility. Radiographs with extractions, restorations, pathologies, caries, severe attrition, root canal treatment, orthodontic appliances were excluded. All images were acquired using standardized protocols and identical radiographic equipment to minimize technical variability.

For each radiograph, the left mandibular second premolar and first molar were evaluated to standardize measurements and avoid duplication of observations from the same individual, yielding 240 teeth (120 premolars and 120 molars). Coronal height (CH) and coronal pulp cavity height (CPCH) were measured using IC Measure software version 2.0.0.245 (Figure 1)[15] and their values were put into the following formula to calculate coronal pulp cavity index (CPCI) [16,17]:

$$\mathrm{CPCI} = \frac{\mathrm{CPCH}}{\mathrm{CH}} \times 100$$

CH was measured as the perpendicular distance from a line connecting the mesial and distal cemento-enamel junctions (cervical line) to the highest point of the occlusal surface (cusp tip). CPCH was measured as the

perpendicular distance from the same cervical reference line to the highest point of the pulp chamber (highest pulp horn) see Figure 1 (c).
All measurements were performed by a trained dentist in dental radiographic analysis. Although inter-observer reliability was not assessed, intra-rater reliability was assessed using intraclass correlation coefficient (ICC; two-way mixed model, absolute agreement). Twelve OPGs were remeasured after one week, yielding ICC values between 0.93 and 0.98, indicating excellent reliability.
Age and gender were recorded along with the CPCH and CH measurements for premolars and molars and CPCI was computed using MS Excel and SPSS version 22. Descriptive statistics i.e. age, CPCH, CH and CPCI were presented as mean ±standard deviation. To check the normality of the data, Shapiro-Wilk test was performed, while residual diagnostics in linear regression included checks for homoscedasticity, QQ plots, and histograms. In order to perform genderbased comparison, Independent T test was performed for the variables that met normality assumptions and Mann Whitney U test for those that did not. Association analysis was carried out using Pearson correlation followed by Uni-and Multivariate regression analyses. In addition to that Standard Error of Estimation (SEE) was also computed. Since this statistic quantifies how closely the predicted values align with actual ages and is calculated as:

$$SEE = \sqrt{\frac{\Sigma\left(Yi - \hat{Y}i\right)2}{n-k-1}}$$

where Y_i is the actual age, $\hat{Y}_i$ is the predicted age from the regression equation, n is the total number of cases, and k is the number of predictors. Lower SEE reflects better overall model fit.
To complement SEE, the mean absolute error (MAE) was also computed, as it provides an intuitive case-wise error estimate relevant for forensic applications.

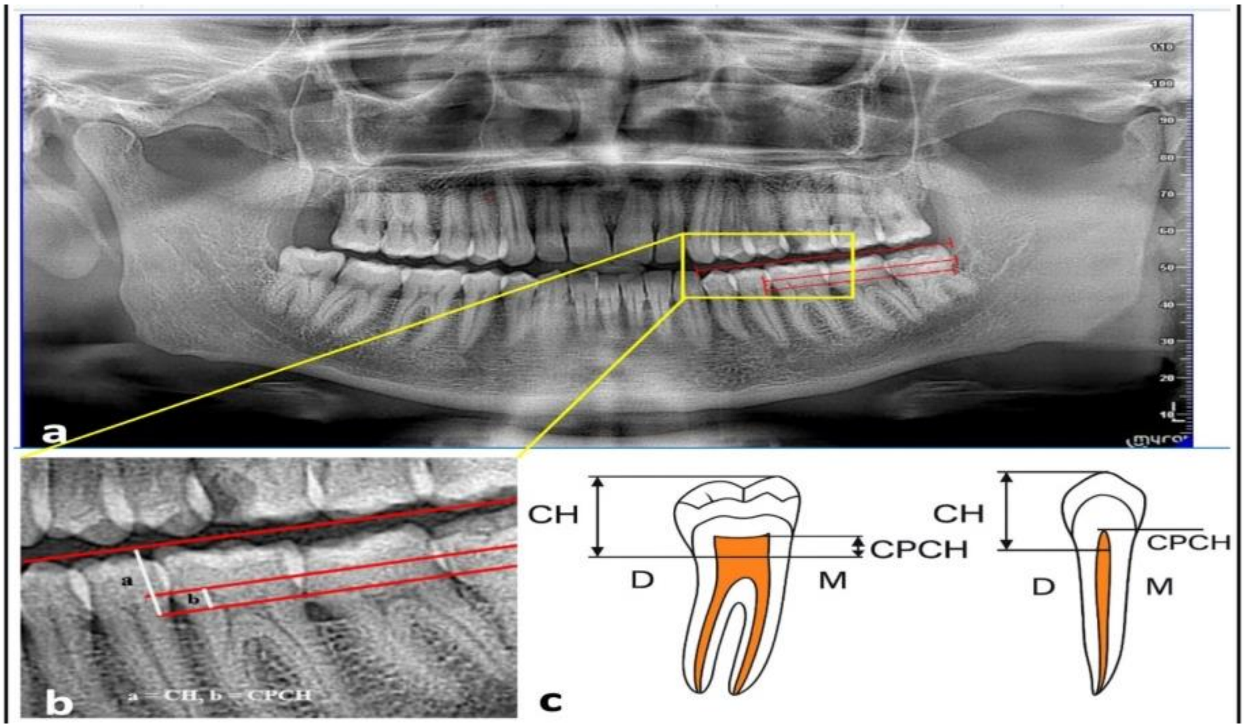

Figure 1: (a) IC Measure software reading an OPG*. b) s*howing measurements taken on a mandibular molar to calculate CPCI*. c)* A diagrammatic representation of calculating CPCI on a premolar and a molar *(CH*: Coronal Height, CPCH: Coronal Pulp Cavity Height, D: Distal, M: Mesial*)*

RESULTS: Out of 120 OPGs, 71 (59.2%) belonged to males and 49 (40.8%) to females. The age ranged from 15 to 75 years with average age of 37.52 ±12.5 years (In males 38.3 ± 12.2 years and females 36.3 ± 13.0 years). The descriptive statistics of the CPCI variables along with their corresponding p values using Shapiro Wilk test are mentioned in the table 1.

Table 1: The descriptive statistics. CH= Coronal Height, CPCH= Coronal Pulp Cavity Height, CPCI= Coronal Pulp Cavity Index * P value significant < 0.05 with 95% confidence interval (CI).

	Mean	SD	Ranges	Shapiro-Wilk P values*
Age (years)	37.51	12.53	15-75	**< .001**
Premolar CH (mm)	6.12	1.1	3.7-7.9	**0.007**
Premolar CPCH (mm)	2.19	0.76	0.7-3.6	**0.005**
Premolar CPCI (mm)	35.03	8.40	14.6-60	0.797
Molar CH (mm)	7.54	0.99	4-9.5	**< .001**
Molar CPCH (mm)	2.97	0.86	1.2-5	0.168
Molar CPCI (mm)	38.87	8.45	20.3-62	0.877
Mean CPCI (mm)	36.95	7.49	19.5-55.4	0.235

Independent T- test/ Mann Whitney U test was performed to determine whether the age and OPG based CPCI variables varied among males and females. The results (table 2) shows that none of the variables varied significantly among males and females.

Table 2: Gender based comparison in terms of mean age, Coronal Pulp Cavity Index (CPCI), premolar and molar measurements (CH, CPCH, CPCI)using independent samples t-test (indicated by single *) and Mann Whitney U test (indicated with double **). P value significant < 0.05 with 95% confidenc interval.

Variables	*p-values*
Age*	0.390
Premolar CH*	0.082
Premolar CPCH*	0.301
Premolar CPCI**	0.700
Molar CH*	0.402
Molar CPCH**	0.421
Molar CPCI**	0.536
Mean CPCI****	0.575

As no significant gender interaction effect was observed, data were pooled across genders to construct a general age estimation model.

Pearson's correlation analysis between age and all measured CPCI variables revealed a strong and statistically significant inverse relationship ($p < .001$). Molar pulp cavity height ($r = –0.859$,) had the strongest negative correlation with age while pre-molar CPCI showed the weakest negative correlation ($r = -0.625$) among the stated variables (Table 3).

Table 3: Representation of Pearson correlation of premolar and molar measurements (CH, CPCH, CPCI, and mean CPCI) with chronological age.* P value significant < 0.05 with 95% confidence interval.

Variables	r (p-value)
Premolar CH	–0.851 (<.001)
Premolar CPCH	–0.841 (<.001)
Premolar CPCI	–0.625 (<.001)
Molar CH	–0.811 (<.001)
Molar CPCH	–0.859 (<.001)
Molar CPCI	–0.688 (<.001)
Mean CPCI	–0.739 (<.001)

To determine the predictive model for age estimation using OPG-based CPCI variables we ran normality diagnostics for the acquired residual errors consisting of checks for homoscedasticity, Q-Q and histogram plots (Figure 2). The residuals were randomly distribution around zero, indicating that the assumptions of linearity and homoscedasticity were met. Most standardized residuals were within the range of ±2, with a few insignificant outliers, confirming that the regression model was appropriate for the data. The histogram and Q-Q plot of standardized residuals showed an approximately normal distribution, with most values lying between ±2 around the mean.

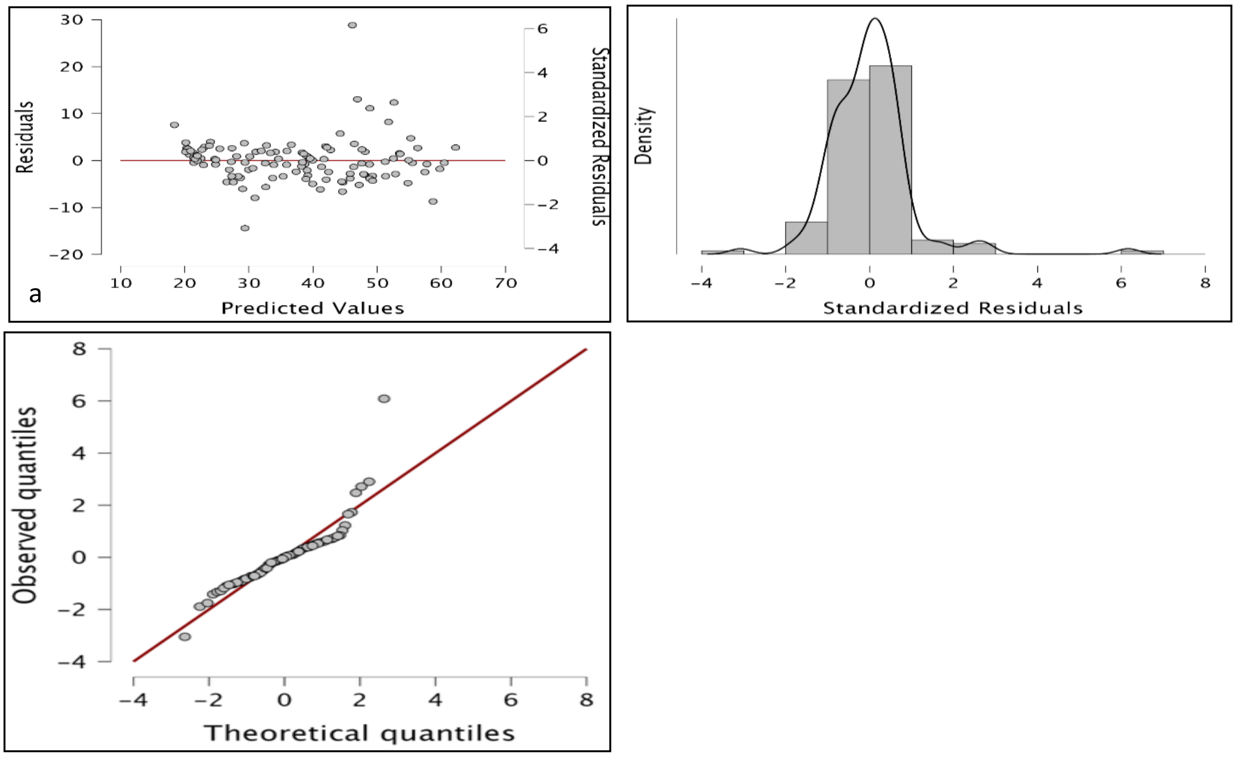

Figure 2:(a) Scatterplot of standardized residuals versus predicted values showing random distribution around zero. (b) Histogram with density curve of standardized residuals approximating a normal distribution.

Initially, univariate regression analyses were performed to examine the individual associations of CPCI variables with and age. The univariate linear regression results are represented by table 3. This regression analysis demonstrated that although all CPCI variables were significantly associated with age ($p < 0.001$), the standard error of estimation ranged from a minimum of ±6.45 years for molar CPCH to ±9.82 years for premolar CPCI. Furthermore, the strength of association varied, with R^2 values ranging from 0.391 (premolar CPCI) to 0.737 (molar CPCH). Among individual predictors, molar CPCH showed the highest explanatory power ($R^2 = 0.737$), accounting for ~74% of age variability, while premolar CPCI showed the lowest ($R^2 = 0.391$) as shown in Table 4.

Table 4: Regression intercept, slope, correlation coefficient (r), coefficient of determination (R^2), and standard error of estimate (SEE) for molars and premolars CH, CPCH and CPCI

Variable	R^2	SEE (years)	p-value
Premolar CH	0.725	6.60	<0.001
Premolar CPCH	0.707	6.81	<0.001
Premolar CPCI	0.391	9.82	<0.001
Molar CH	0.658	7.35	<0.001
Molar CPCH	0.737	6.45	<0.001
Molar CPCI	0.473	9.13	<0.001
Mean CPCI	0.546	8.48	<0.001

The multivariate regression model incorporating premolar and molar CH, CPCH, and CPCI variables is summarized in Table 5. Among all predictors, only premolar CPCH showed a statistically significant association with age (B = –12.657, β = –0.772, p = 0.030). None of the other predictors (premolar CH, premolar CPCI, molar CH, molar CPCH, or molar CPCI) retained statistical significance in the multivariate model ($p > 0.05$). The overall model intercept was 79.157 ($p < 0.001$) while the model's predictive error was low (SEE = 4.83 years).

Table 5: Multiple linear regression coefficients for predicting chronological age from premolar and molar indices with 95% confidence interval and p-value < 0.05.

Coefficients					
Predictor	**B (Unstd.)**	**SE**	**β (Std.)**	**t**	**p**
Intercept	79.157	17.62	–	4.492	< .001
Premolar CH	0.304	2.098	0.027	0.145	0.885
Premolar CPCH	–12.657	5.722	–0.772	–2.212	0.030
Premolar CPCI	0.596	0.339	0.400	1.760	0.081
Molar CH	–2.918	2.276	–0.231	–1.282	0.202
Molar CPCH	–5.165	6.490	–0.353	–0.796	0.428
Molar CPCI	0.017	0.479	0.011	0.035	0.972

The standard error of estimate (SEE) of 4.8 years for the regression model indicated the overall dispersion of observed ages around the regression line. For MAE, predicted ages were calculated using the regression equation:

Predicted Age = 79.065+0.310(Premolar CH) −12.572(Premolar CPCH) +6.686(Premolar CPCI) − 2.923(Molar CH) − 5.250(Molar CPCH) +6.128(Molar CPCI)

Residuals were obtained as $e_i = Y_i - \hat{Y}_i$

Because residuals may be positive or negative, absolute values were taken to avoid cancellation. The MAE was then computed as:

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |\mathbf{Yi} - \hat{\mathbf{Y}}\mathbf{i}|$$

where Y_i is the actual age, $\hat{Y}_i$ is the predicted age from the regression equation, n is the total number of cases. MAE was approximately **±**3.0 years, representing the average prediction error per individual.

Following the multiple linear regression analysis, multicollinearity diagnostics were assessed to evaluate relationships among the predictor variables. Tolerance values ranged from 0.006 to 0.038, while variance inflation factor (VIF) values ranged from 26.13 to 158.28, indicating substantial multicollinearity among the predictors. The observed collinearity was expected because CPCI is mathematically derived from CH and CPCH measurements. Consequently, although several variables demonstrated strong individual associations with age, their independent contributions were reduced in the multivariable regression model due to shared variance among predictors.

DISCUSSION: This study evaluated the forensic accuracy of the Coronal Pulp Cavity Index (CPCI) for the estimation of chronological age in Pakistani adults using OPG measurements of mandibular molars and premolars. The CPCI showed a strong inverse correlation with age. Furthermore, molar measurements particularly molar CPCH provided high predictive accuracy (R^2= 0.737) compared to premolars, supporting their suitability for forensic application. The multivariate model significantly improved prediction accuracy (SEE=4.8 years, MAE= 3 years), underscoring the value of incorporating multiple radiographic parameters for estimating age. These findings confirm CPCI as a robust, non-invasive, and statistically validated tool for forensic age estimation, while providing the first population-specific regression equations for the Pakistani population that can enhance medico-legal identification in South Asia.

In the present study, males formed the majority (59.2%) compared to females (40.8%). A similar male predominance was reported in Indian and Egyptian populations [19,20]. whereas European investigations reported more balanced gender distributions [18]. The higher proportion of males in our sample may reflect sociocultural and healthcare-seeking patterns in Pakistan.

With respect to age, our participants were largely concentrated in the younger and middle-aged groups, with 34.2% aged 15–29 years and 35.0% aged 30–44 years similar to Indianand Egyptian studies [19,20]. One possible explanation is that individuals in these age groups are more likely to seek dental radiographs for orthodontic, restorative, or minor oral surgical procedures, thereby increasing their representation in radiographic archives. European investigations included broader age ranges due to differences in healthcare systems and preventive practices [18].

The multivariate linear regression equation based on CPCI estimated age with an average error (SEE) of approximately 4.8 years and a mean absolute error (MAE) of 3.0 years, consistent with previous studies. Indian studies reported SEE values of 5–6.6 years, whereas Brazilian studies reported 1–3 years [12,21]. Differences may reflect population-specific variations in dental development and secondary dentin deposition [14,21]. Variations in radiographic quality and consistency of measurement methods may also contribute to increased error [21].

Furthermore, CPCI demonstrated a significant negative correlation with age, indicating that CPCI decreases as age increases due to progressive secondary dentin deposition and reduction of pulp cavity size. This trend has been reported in Egyptian and European populations [22–24]. with molars showing stronger age-related changes because of larger pulp chambers and functional loading [13]. However, some studies reported increased CPCI with age, possibly due to younger sample populations where dentin deposition is not yet linear [25]. When comparing predictor categories, direct measurements such as coronal height (CH) and coronal pulp cavity height (CPCH) consistently outperformed ratio-based indices like CPCI, similar to previous studies [26]. Collectively, these findings reinforce that CPCI remains useful in population studies, whereas absolute coronal dimensions may provide more stable indicators for individual age estimation [27].

Interestingly, the molars gave better predictive values for age than the premolars consistent with Egyptian, Indian and Iranian populations [12,20,28]. This is because larger pulp chambers and clearer anatomical landmarks of molars improve measurement reliability, while premolars may have less distinct pulp boundaries

[13] . The anatomical landmarks in molars are often easier to identify reliably, reducing technical errors during measurement [13,20].

Despite methodological rigor, limitations include modest sample size, bicentric study, absence of inter-rater reliability assessment, underrepresentation of elderly subjects, potential manual measurement error, and distortion inherent to OPG imaging. Future research should include multicentric Pakistani cohorts, larger sample size, broader age ranges, incorporation of balanced age ranges, assessment of both intra- and inter-examiner reliability and employ advanced multivariate models.

CONCLUSION: The findings suggest that CPCI may serve as a useful adjunctive method for forensic age estimation in Pakistani adults, particularly when multiple radiographic parameters are combined. However, because the study was conducted in only two institutions and included a relatively limited sample, the derived regression equations should be externally validated before broader application. CPCI should therefore be considered a complementary rather than a standalone forensic age estimation technique. Development of population-specific regression models remains essential to maximize accuracy and applicability.

Abbreviations:
CPCI: Coronal Pulp Cavity Index
CH: Coronal Height
CPCH: Coronal Pulp Cavity Height
OPG: Orthopantomogram
IOPA: Intra Oral Peri Apical
KCD: Khyber College of Dentistry
RCD: Rehman College of Dentistry
OMFS: Oral and Maxillofacial Surgery
ICC: Intraclass Correlation Coefficient
SEE: Standard Error of Estimation
MAE: Mean Absolute Error

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