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ORIGINAL ARTICLE

Population-specific age estimation in Black Americans and Chinese people based on pulp chamber volume of first molars from cone beam computed tomography

Han Du[1] · Gang Li[1] · Qiang Zheng[2] · Jie Yang[3]

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Abstract

Objectives To validate the fitness of the age estimation model in Black Americans, which was previously and solely established for the Chinese population based on pulp chamber volume of the first molars from cone beam computed tomography (CBCT), and to establish a new age estimation model for Black Americans.

Materials and methods A total of 203 subjects with CBCT scans, including 119 Chinese and 84 Black Americans, were retrospectively identified. The age range of subjects was between 11 and 87 years. For both populations, automated 3D pulp chamber segmentation of the first molars was performed by deep learning, followed by volume calculation and age estimation by a logarithmic regression model, which was established in a prior study solely on Chinese population. Additionally, a separate logarithmic regression analysis was carried out on Black Americans. The performance of age estimation was assessed by the mean absolute error (MAE), root mean square error (RMSE), Wilcoxon signed rank test, and coefficient of determination (R^2) between the actual and estimated human ages.

Results When applying the age estimation model established in the prior study, MAE = 7.994 years and RMSE = 10.065 years were observed in the Chinese population, while MAE = 14.049 years and RMSE = 17.866 years were observed in Black Americans. The new age estimation model established for Black Americans was AGE = $89.752 - 21.176 \times \ln V$ (V = pulp chamber volume), with MAE = 7.930 years, RMSE = 10.664 years, and coefficient of determination (R^2) = 0.600.

Conclusions Population-specific age estimation is needed when applied in Black Americans and Chinese people based on pulp chamber volume of the first molars from CBCT.

Keywords Age estimation · Pulp chamber volume · Cone beam CT · Forensic anthropology

Introduction

Age estimation is one of the important methods used in forensic science for narrowing suspected victims. It is common knowledge that teeth and their surrounding structures are extremely resistant to destruction for a long time than any other body parts following death and are often used for age estimation [1]. Analysis of tooth development stage helps in age estimation in children and adolescents but does not apply to adults [2]. Gustafson was the first to report the narrowing of the pulp cavity due to secondary dentin formation for age estimation [3]. Philippas [4] found that the formation of secondary dentine continues throughout life regardless of the degree of occlusal wear.

Many studies have used pulp chamber size or pulp/tooth ratio to estimate human age using dental radiographs [5–10]. Kvaal et al. described a method for age estimation by linear measurement of radiographic pulp, teeth, and roots. The results demonstrated a strong correlation between actual age and the ratios of pulp, roots, and teeth [5]. Since then, length, width, and area measurements of the pulp cavity or pulp/tooth ratio in 2D imaging have been widely used as

✉ Gang Li
kqgang@bjmu.edu.cn

[1] Department of Oral and Maxillofacial Radiology, Peking University School and Hospital of Stomatology, #22 Zhongguancun Nandajie, Hai Dian District, Beijing 100081, China

[2] School of Computer and Control Engineering, Yantai University, Yantai, China

[3] Division of Oral and Maxillofacial Radiology, Temple University Kornberg School of Dentistry, Philadelphia, PA, USA

an age estimation method [6–10]. However, the age estimation model obtained from one region or ethnic population cannot be directly applied to other regions or ethnic populations. For instance, the popularly used age estimation method, developed by Cameriere et al., was found to be not universally accurate. Studies have shown that when Cameriere's method is applied to people in different countries and regions for age estimation, the standard error of estimate varies considerably from 3.05 to 13.08 [11–14].

With the wide use of three-dimensional images in practice, cone beam CT (CBCT), CT, and micro-CT image datasets have been applied to age estimation by using pulp chamber volume or the ratio of pulp cavity to the entire tooth in mono- or multi-radicular teeth [1, 15–20]. Many age estimation models have been established from CBCT image datasets so that human age can be estimated exclusively from respective population [1, 15–19]. Recently, we developed one age estimation model with the help of deep learning techniques to segment the pulp chamber volume and found that it is accurate enough for age estimation, with a mean absolute error (MAE) = 7.26 years and root mean square error (RMSE) = 9.00 years in the Chinese population [21].

To date, it is well known that an age estimation model derived from two-dimensional dental images of one population may not be applicable to another population. This is most probably due to the population differences and/or the 2D projection of 3D structures of teeth.

The 2D projection of 3D structures might obfuscate and/or distort certain anatomical details and might result in nuancing of the findings.

Inter- and intra-observer variability of segmentation may further be overcome by automated segmentation of pulp chamber volumes with deep learning techniques. With these hypotheses in mind, people may still wonder whether the age estimation model obtained from one specific population by deep learning techniques on three-dimensional images is applicable to another population.

The aim of the present study was thus to evaluate whether the age estimation model solely obtained from the Chinese population is still suitable for age estimation in Black Americans. If not, a new age estimation mathematical model exclusively for Black Americans would be established and evaluated.

Materials and methods

This retrospective study was approved by the Institutional Review Board, and the requirement for written informed consent was waived.

CBCT images of 161 maxillary first molars and 159 mandibular first molars were retrospectively collected from 119 Chinese patients aged between 11 and 69 years old (Table 1).

Table 1 Age and sex distribution of Chinese used in estimating human age

Age	Number	Male	Female	Maxillary first molars	Mandibular first molars
11–20	20	9	11	36	36
21–30	30	12	18	37	38
31–40	19	8	11	26	23
41–50	20	11	9	27	24
51–60	23	14	9	30	29
> 60	7	4	3	5	9
Total	119	58	61	161	159

Table 2 Age and sex distribution of Black Americans used in estimating human age

Age	Number	Male	Female	Maxillary first molars	Mandibular first molars
11–20	23	9	14	34	26
21–30	24	8	16	30	23
31–40	11	8	3	12	9
41–50	10	4	6	10	8
51–60	11	8	3	13	11
> 60	5	2	3	6	3
Total	84	39	45	105	80

The CBCT images of Black Americans were collected from patients aged 11 to 87 years, and a total of 105 maxillary first molars and 80 mandibular first molars were included (Table 2). The inclusion criteria of the first molars were as follows: no caries, no excessive tooth wear, no dental restorations, no artifacts from metal restorative materials present in adjacent teeth, and no pulpal calcification. All maxillary and mandibular first molars were included for analysis as long as they were available in CBCT images.

All CBCT images of Chinese patients were obtained with a CBCT unit NewTom VG (Quantitative Radiology, Verona, Italy), and the exposure parameters were 110 kVp and 3.6–270 mAs, in accordance with patient size and field of view. Based on clinical needs, the scanned field of view included 8 × 8 cm, 12 × 8 cm, 15 × 12 cm, and 15 × 15 cm. All CBCT images of Black American patients were obtained with a ProMax 3D CBCT unit (Planmeca Oy, Helsinki, Finland), and the exposure parameters were 90–120 kVp and 9–110.1 mAs, in accordance with patient size and field of view.

Prior to segmentation of the 3D pulp chamber by deep learning, the extraction of target first molar was conducted by a minimally interactive strategy, which was established with a three-step delineation. After the procedure of image segmentation, the pulp chamber was extracted (Fig. 1),

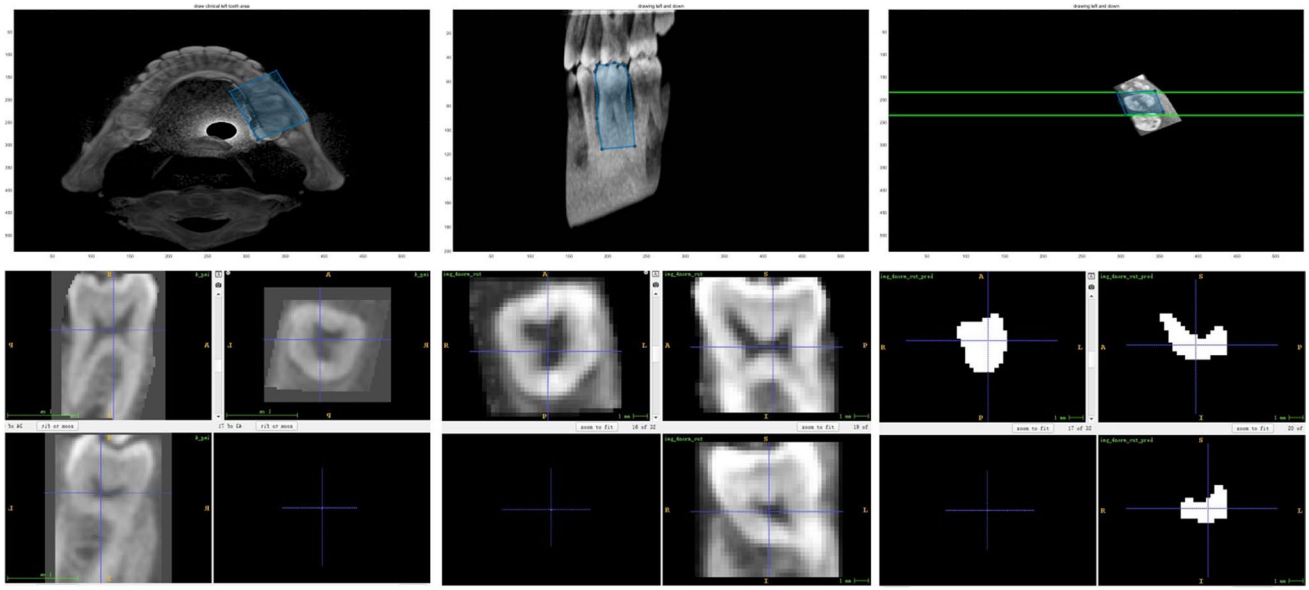

Fig. 1 The final segmented image of the tooth pulp chamber

Table 3 Linear regression model for age estimation established in the previous study from Chinese samples

	Linear regression model
All teeth	$AGE = 134.6 - 32.7 \times \ln V$
Maxillary first molar	$AGE = 132.3 - 31.8 \times \ln V$
Mandibular first molar	$AGE = 138.2 - 34.0 \times \ln V$

All teeth: maxillary first molar or mandibular first molar

and the volume of the tooth pulp chamber was calculated. Detailed information can be found in previous study [21].

Following the procedure mentioned above, the pulp chamber volumes from a new group of Chinese population and Black Americans were obtained and subsequently used to estimate the ages of Chinese and Black Americans by the age estimation model established in the previous study solely on Chinese samples (Table 3).

Mean absolute error and root mean square error between actual and estimated ages were used to evaluate the accuracy of the age estimation model in Black Americans and Chinese population, respectively.

To develop a new age estimation model exclusively for the Black American population, logarithmic regression analysis was conducted with age as the dependent variable and pulp chamber volume of all teeth of Black Americans as the independent variable.

The fivefold cross-validation (CV) method was used to prevent overfitting of the dataset. First, the dataset was split into five parts, which preserved the distribution of ages and the proportion of males and females in each part. Then, two different datasets were built in each CV iteration: the establishing mathematical model dataset and the test dataset. The model set was composed of four parts of the dataset, and the test dataset comprised the fifth part. Finally, the model performance could be assessed in the union of the five test datasets obtained by CV, which corresponded to the entire dataset.

The Wilcoxon signed rank test was adopted to compare actual and estimated human ages, with $P > 0.1$ being no significant difference. Additionally, the coefficient of determination (R^2), MAE, RMSE, and correlation coefficient (r) between the actual and estimated ages were used to assess the accuracy of the new age estimation model for Black Americans.

Analysis of covariance (ANCOVA) was then applied to study possible interactions between age, pulp chamber volume, and ethnicity. Statistical analysis was performed using SPSS Statistics 26.0 (SPSS, IBM Corp., Chicago, IL).

Results

For all teeth from Chinese samples, the pulp chamber volumes ranged from 8.758 to 50.828 mm^3 with a mean value of 23.867 mm^3 (SD = 7.769), while the pulp chamber volumes of Black Americans ranged from 2.268 to 45.704 mm^3 with a mean volume of 18.610 mm^3 (SD = 9.075). The volumes distributed in each age section are shown in Fig. 2 for both Chinese and Black Americans.

Figure 3 shows the relationship between the actual age and age estimated with the model established solely from

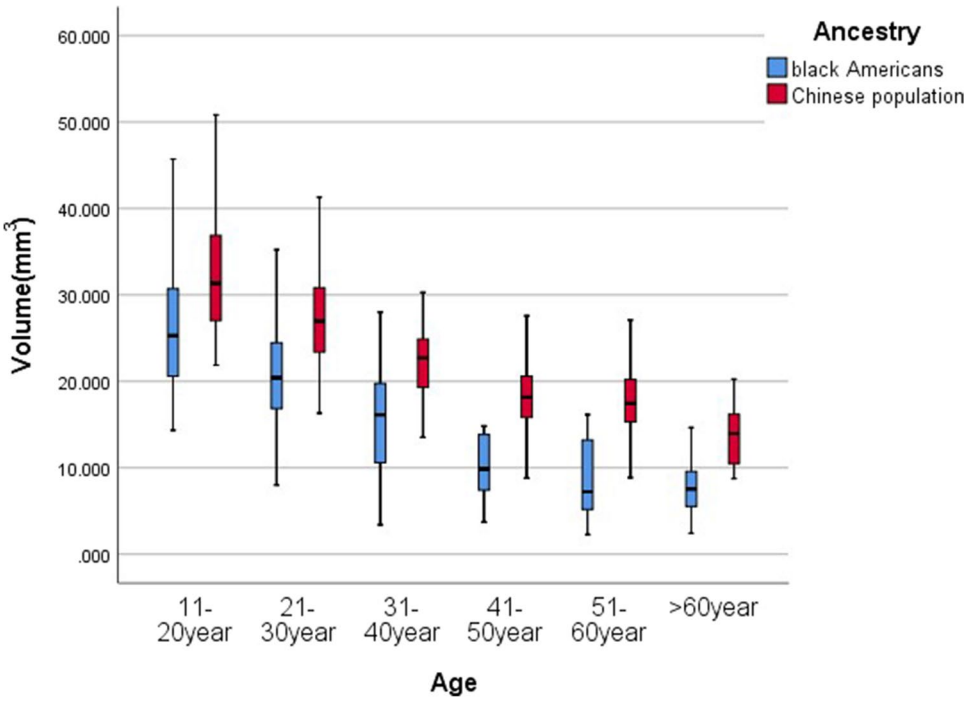

Fig. 2 The distribution of pulp chamber volume in different age groups of Black Americans and Chinese

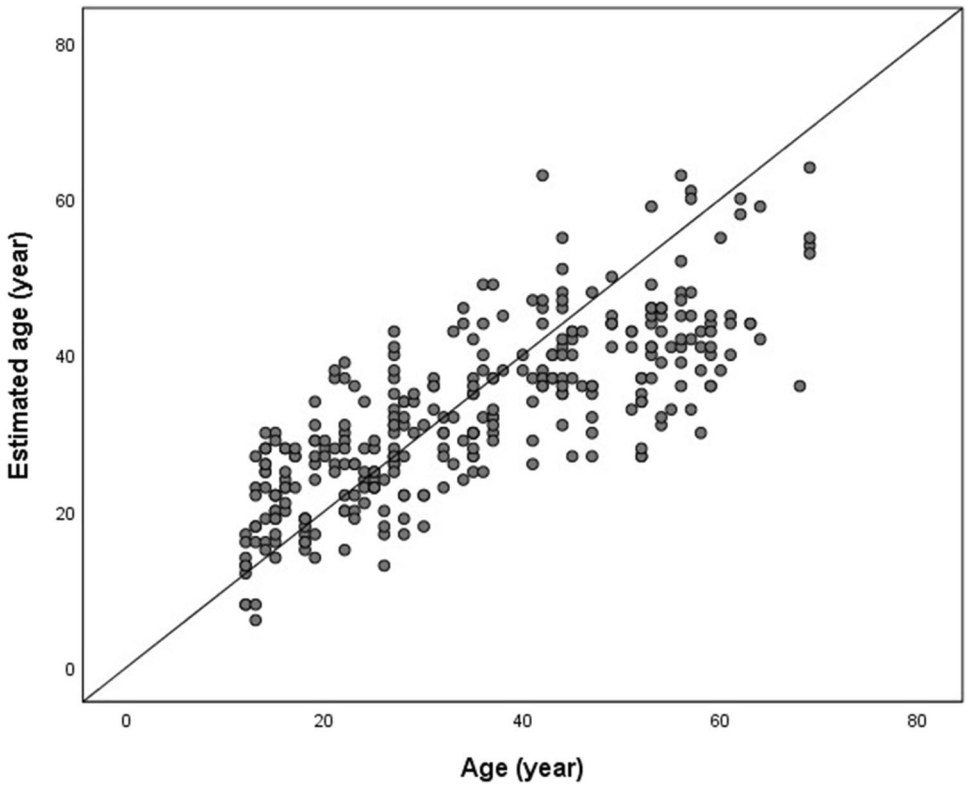

Fig. 3 Plot of actual age versus estimated age for teeth of the Chinese population using the age estimation model established from Chinese samples

Chinese samples in the previous study. The MAE was 7.994 years, and RMSE was 10.065 years.

Figure 4 shows the relationship between the actual age and the age estimated with the model established solely from Chinese samples for Black Americans. The MAE was 14.049 years, and RMSE was17.866 years.

The logarithmic regression model for age estimation of Black Americans was as follows:

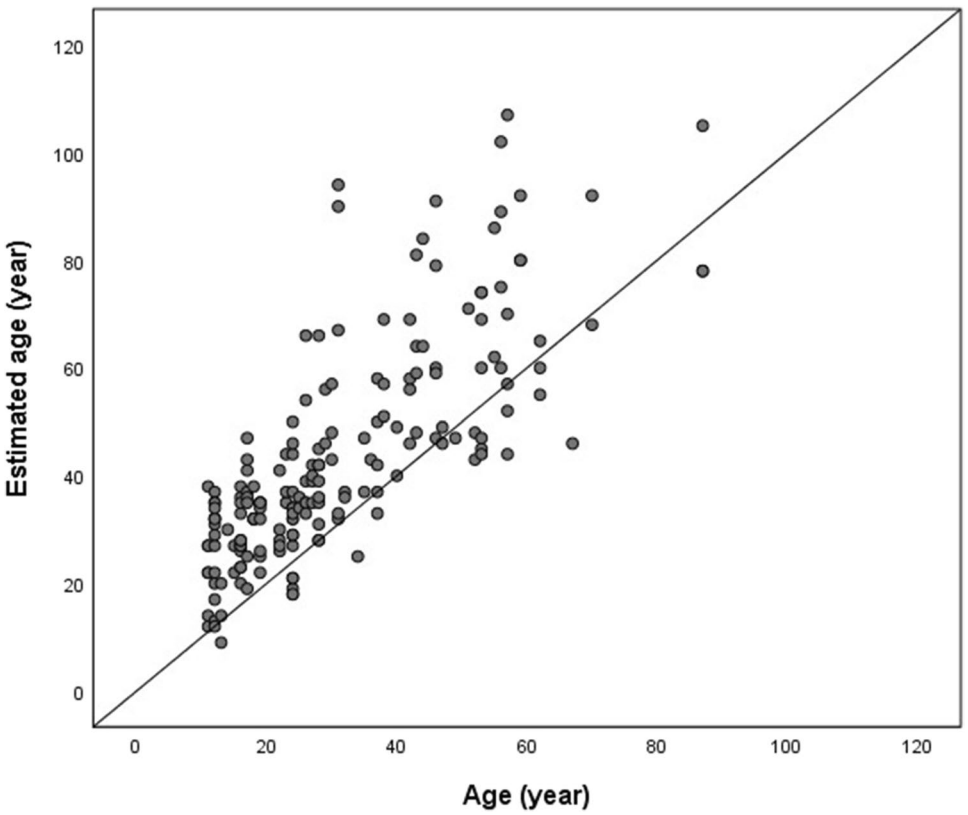

Fig. 4 Plot of actual age versus estimated age for all teeth of Black Americans using the age estimation model established from Chinese samples

$AGE = 89.752 - 21.176 \times \ln V$ (V = pulp chamber volume, mm^3).

A scatter plot of the pulp chamber volumes versus actual ages for Black Americans is shown in Fig. 5.

There was no significant difference between the estimated and actual human ages ($P = 0.406 > 0.1$). MAE was 7.930 years, RMSE was 10.664, R^2 was 0.600, and r was 0.775.

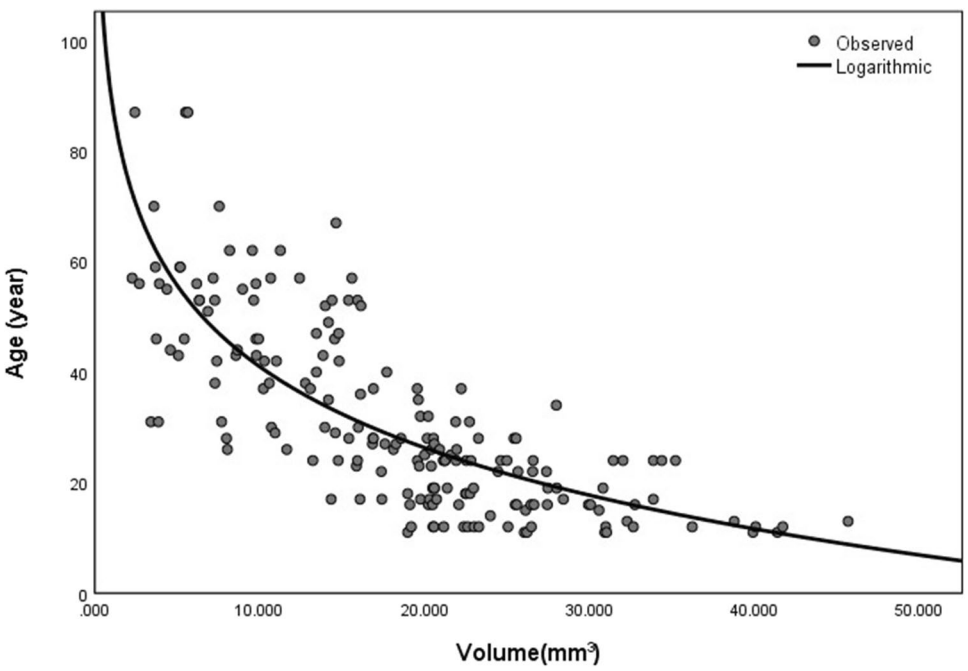

Fig. 5 Scatter plot shows the relationship between the volumes of pulp chamber and actual ages for all teeth of Black Americans

When using the fivefold cross-validation (CV) method, there was no significant difference between the estimated and actual human ages ($P = 0.426 > 0.1$). The MAE was 7.941 years, RMSE was 10.722. No significant difference was found between the estimated ages which were calculated after using the fivefold CV method, and those obtained only with the above equation ($P = 0.952$).

Plot of actual age versus estimated age with a logarithmic regression model for all teeth of Black Americans is shown in Fig. 6. The data are symmetrically scattered around the diagonal line, which is the line of identity.

Plot of actual age versus estimation age with the logarithmic regression model obtained from Black Americans for the Chinese population is shown in Fig. 7. MAE was 12.325 years and RMSE was 15.296 years.

For the pulp chamber volumes of the first molars, ANCOVA (Table 4) revealed a significant difference in the intercept between Black Americans and the Chinese population ($P < 0.05$). The estimated parameters are listed in Table 5. The data were consequently fitted according to the following logarithmic model:

$$\mathrm{AGE} = 103.563 + 12.897 \times E - 26.166 \times \ln V$$

where binary variable E represents an individual's ethnicity and is assigned a value of 1 if the individual is Chinese and

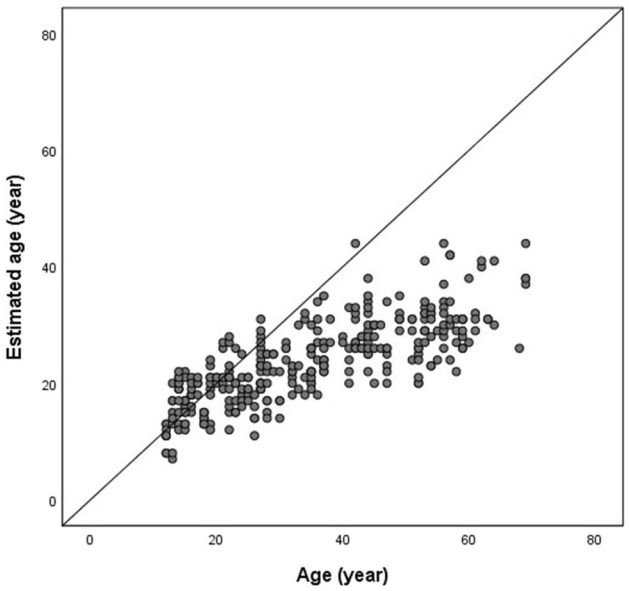

Fig. 7 Plots of actual age versus estimated age with the new age estimation model from Black Americans for all teeth of Chinese

Fig. 6 Plots of actual age versus estimated age with logarithmic regression model for all teeth of Black Americans

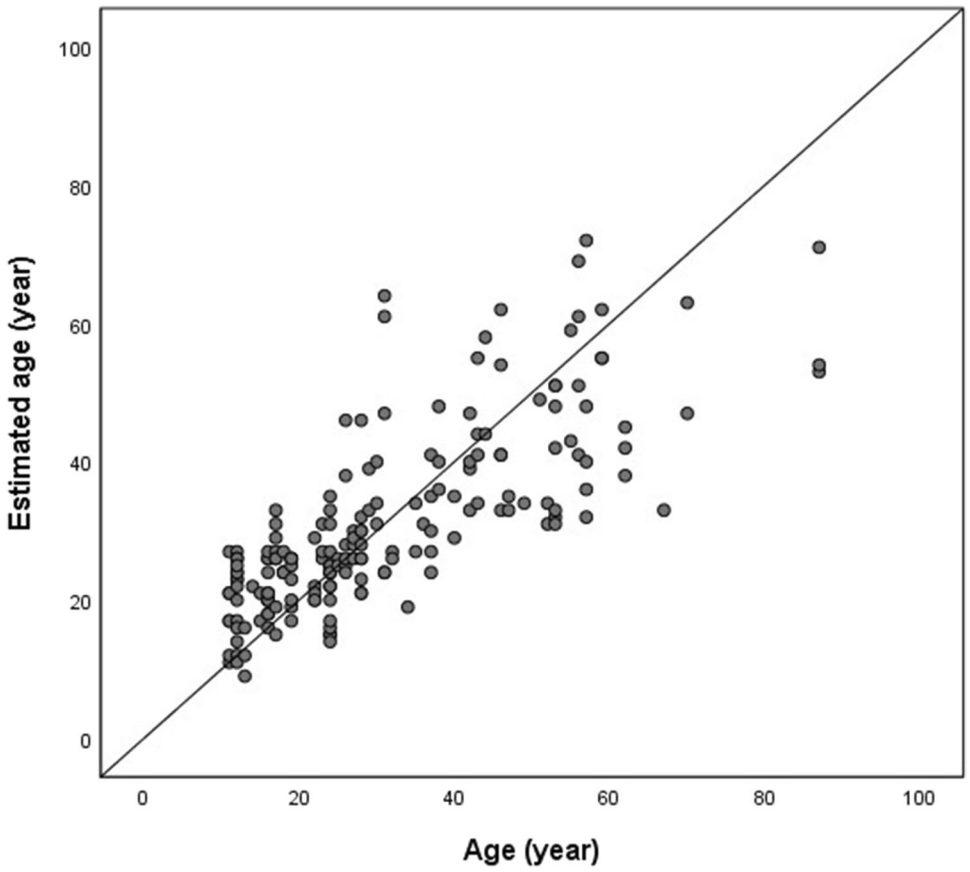

Table 4 ANCOVA table

	df	SS	MS	*F* value	*P*
Volume	1	74,752.082	74,752.082	686.426	< 0.001
Ethnicity	1	14,089.580	14,089.580	129.380	< 0.001
Residuals	502	54,668.028	108.900	–	–

ANCOVA analysis of covariance, *df* degree of freedom, *SS* sum of squares of deviation from mean, *MS* mean square

Table 5 Regression analysis predicting human age from first molars

Coefficients*	Value	Std. error	*t* value	*P*
β_0	103.563	2.958	35.007	< 0.001
β_1	12.897	1.046	12.334	< 0.001
β_2	− 26.166	1.031	− 25.383	< 0.001

*$\mathrm{AGE} = \beta_0 + \beta_1 \times E + \beta_2 \times \ln V$

0 if the individual is a Black American, and *V* represents the pulp chamber volume of the first molars.

There was no significant difference between the estimated and actual human ages ($P = 0.543 > 0.1$). MAE was 8.434 years, and RMSE was 10.614.

Discussion

Secondary dentine deposition is an age-associated process. Since it is along the internal surface of the tooth, secondary dentine is considered well protected against environmental influences. This is why the pulp chamber volume can be used to estimate human ages. To predict the accuracy of the estimated age, MAE and RMSE, which are calculated from actual and estimated ages, respectively, are often used as indicators.

The present study shows that when using the age estimation model obtained from the Chinese population to estimate the ages of a Chinese sample, MAE (7.994 years) and RMSE (10.065 years) were reasonable and similar to the values from a previous study [21]. However, when the same age estimation model was applied to Black Americans, both MAE (14.049 years) and RMSE (17.866 years) were over 10 years, which is unacceptable for age estimation in forensic science [17]. A similar result was obtained when the age estimation model established from Black Americans was applied to a Chinese population for age estimation. This means that the age estimation model obtained from the Chinese population with three-dimensional images cannot be used to estimate the ages of Black Americans and vice versa. The reason may be explained by the different pulp chamber volumes from the two populations, as shown in Fig. 2. Generally, the pulp chamber volume of the Chinese population is larger than that of Black Americans. This leads to an underestimation of the ages of Black Americans when using the model from the Chinese population, as shown in Fig. 4, and overestimated ages of the Chinese population by the models obtained from Black Americans (Fig. 7). In this sense, the volume is the key for age estimation when a dental pulp chamber is employed.

The results showed that when using the age estimation model obtained from Black Americans to estimate the ages of Black Americans, MAE was 7.930 years, and RMSE was 10.664 between the actual and estimated ages. When the present study is compared with the studies by Jagannathan et al. (MAE of 8.54 in the mandibular canines) [17] and by Asif et al. (MAE of 6.48 in the maxillary incisor and MAE of 8.58 in the maxillary canines) [22], a similar discrepancy between the estimated and actual ages was found as in the present study. In this study, a relatively high coefficient of determination was demonstrated for the pulp chamber volume of the first molar and age of Black Americans with $R^2 = 0.600$. Adisen et al. [23] used the pulp/tooth volumes of maxillary canines to estimate age, and R^2 was 0.347. The results from Kazmi et al. [24] showed that mandibular canine pulp volume and sex had the highest predictive power in the six introduced models ($R^2 = 0.33$). Molina et al. [25] used the pulp chamber/crown volume ratio of incisors, canines, and lower premolars to estimate age and obtained R^2 ranging from 0.010 to 0.366 based on different tooth positions. These differences may be due to the variability in pulp volume between individuals and different types of teeth. The more dispersed the pulp chamber volumes of individuals within the same age group, the less accurate age estimations can be obtained.

There are few limitations in our study. One is that only the first molars were included. This may limit the use of the developed model for age estimation, especially for older people. Future investigations will use pulp volume and hard tooth structure information from uni-radicular and multi-radicular teeth to estimate human age. Meanwhile, future investigations can examine a more advanced deep learning model for age estimation based on Black Americans. Second, the performance of age estimation needs to be further improved by collecting a larger sample and taking the sex distribution for each age group into account.

Conclusion

In summary, our study demonstrated that there are anthropological differences in pulp chamber volumes between various ethnic populations and further justified that application of the population-specific age estimation models is necessary. The pulp chamber volumes of the first molars derived

from CBCT images by the deep learning method could be effectively used to estimate human ages.

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Declarations

Ethical approval All procedures performed in the study involving human participants were in accordance with the ethical standards of the Institutional Review Board and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Written informed consent was not required for this study because all the included patients in the present investigation were collected retrospectively. Exemption of informed consent will not affect the rights and health of the included patients. The application for free informed consent was approved by the Institutional Review Board.

Conflict of interest The authors declare no competing interests.

References

1. Someda H, Saka H, Matsunaga S, Ide Y, Nakahara K, Hirata S, Hashimoto M (2009) Age estimation based on three-dimensional measurement of mandibular central incisors in Japanese. Forensic Sci Int 185(1–3):110–114. https://doi.org/10.1016/j.forsciint.2009.01.001
2. Panchbhai AS (2011) Dental radiographic indicators, a key to age estimation. Dentomaxillofac Radiol 40(4):199. https://doi.org/10.1259/dmfr/19478385
3. Gustafson G (1950) Age determination on teeth. J Am Dent Assoc 41(1):45–54. https://doi.org/10.14219/jada.archive.1950.0132
4. Philippas G (1961) Influence of occlusal wear and age on formation of dentin and size of pulp chamber. J Dent Res 40(6):1186–1198. https://doi.org/10.1177/00220345610400061301
5. Kvaal SI, Kolltveit KM, Thomsen IO, Solheim T (1995) Age estimation of adults from dental radiographs. Forensic Sci Int 74(3):175–185. https://doi.org/10.1016/0379-0738(95)01760-g
6. Gok E, Fedakar R, Kafa IM (2020) Usability of dental pulp visibility and tooth coronal index in digital panoramic radiography in age estimation in the forensic medicine. Int J Legal Med 134(1):381–392. https://doi.org/10.1007/s00414-019-02188-w
7. Suvarna M, Balla SB, Chinni SS, Reddy KSP, Gopalaiah H, Pujita C, Reddy RN (2020) Examination of the radiographic visibility of the root pulp of the mandibular second molars as an age marker. Int J Legal Med 134(5):1869–1873. https://doi.org/10.1007/s00414-020-02347-4
8. Balla SB, Ankisetti SA, Bushra A, Bolloju VB, Mujahed AM, Kanaparthi A, Buddhavarapu SS (2020) Preliminary analysis testing the accuracy of radiographic visibility of root pulp in the mandibular first molars as a maturity marker at age threshold of 18 years. Int J Legal Med 134(2):769–774. https://doi.org/10.1007/s00414-020-02257-5
9. Cameriere R, Ferrante L, Cingolani M (2004) Variations in pulp/tooth area ratio as an indicator of age: a preliminary study. J Forensic Sci 49(2):317–319. https://doi.org/10.1520/JFS2003259
10. Cameriere R, Cunha E, Wasterlain SN, De Luca S, Sassaroli E, Pagliara F, Nuzzolese E, Cingolani M, Ferrante L (2013) Age estimation by pulp/tooth ratio in lateral and central incisors by peri-apical X-ray. J Forensic Leg Med 20(5):530–536. https://doi.org/10.1016/j.jflm.2013.02.012
11 Cameriere R, Cunha E, Sassaroli E, Nuzzolese E, Ferrante L (2009) Age estimation by pulp/tooth area ratio in canines: study of a Portuguese sample to test Cameriere's method. Forensic Sci Int 193(1–3):128.e1-128.e6. https://doi.org/10.1016/j.forsciint.2009.09.011
12. Marroquin TY, Karkhanis S, Kvaal SI, Vasudavan S, Kruger E, Tennant M (2017) Age estimation in adults by dental imaging assessment systematic review. Forensic Sci Int 275:203–211. https://doi.org/10.1016/j.forsciint.2017.03.007
13. Zaher JF, Fawzy IA, Habib SR, Ali MM (2011) Age estimation from pulp/tooth area ratio in maxillary incisors among Egyptians using dental radiographic images. J Forensic Leg Med 18(2):62–65. https://doi.org/10.1016/j.jflm.2010.12.004
14 Babshet M, Acharya AB, Naikmasur VG (2010) Age estimation in Indians from pulp/tooth area ratio of mandibular canines. Forensic Sci Int 197(1–3):125.e1-125.e4. https://doi.org/10.1016/j.forsciint.2009.12.065
15. Tardivo D, Sastre J, Catherine JH, Leonetti G, Adalian P, Foti B (2014) Age determination of adult individuals by three-dimensional modelling of canines. Int J Legal Med 128(1):161–169. https://doi.org/10.1007/s00414-013-0863-2
16. Star H, Thevissen P, Jacobs R, Fieuws S, Solheim T, Willems G (2011) Human dental age estimation by calculation of pulp-tooth volume ratios yielded on clinically acquired cone beam computed tomography images of monoradicular teeth. J Forensic Sci 56:S77–S82. https://doi.org/10.1111/j.1556-4029.2010.01633.x
17. Jagannathan N, Neelakantan P, Thiruvengadam C, Ramani P, Premkumar P, Natesan A, Herald JS, Luder HU (2011) Age estimation in an Indian population using pulp/tooth volume ratio of mandibular canines obtained from cone beam computed tomography. J Forensic Odontostomatol 29(1):1. https://doi.org/10.5167/uzh-49946
18. Sakuma A, Saitoh H, Suzuki Y, Makino Y, Inokuchi G, Hayakawa M, Yajima D, Iwase H (2013) Age estimation based on pulp cavity to tooth volume ratio using postmortem computed tomography images. J Forensic Sci 58(6):1531–1535. https://doi.org/10.1111/1556-4029.12175
19. Ge ZP, Ma RH, Li G, Zhang JZ, Ma XC (2015) Age estimation based on pulp chamber volume of first molars from cone-beam computed tomography images. Forensic Sci Int 253(133):e131-137. https://doi.org/10.1016/j.forsciint.2015.05.004
20. Porto LVMG, Neto JCD, Pontual AD, Catunda RQ (2015) Evaluation of volumetric changes of teeth in a Brazilian population by using cone beam computed tomography. J Forensic Leg Med 36:4–9. https://doi.org/10.1016/j.jflm.2015.07.007
21. Zheng Q, Ge Z, Du H, Li G (2021) Age estimation based on 3D pulp chamber segmentation of first molars from cone-beam–computed tomography by integrated deep learning and level set. Int J Legal Med 135(133):1–9. https://doi.org/10.1007/s00414-020-02459-x
22. Asif MK, Nambiar P, Mani SA, Ibrahim NB, Khan IM, Lokman NB (2019) Dental age estimation in Malaysian adults based on

volumetric analysis of pulp/tooth ratio using CBCT data. Leg Med 36:50–58. https://doi.org/10.1016/j.legalmed.2018.10.005
23. Adisen MZ, Keles A, Yorubulut S, Nalcaci R (2018) Age estimation By measuring maxillary canine pulp/tooth volume ratio on cone beam CT images with two different voxel sizes. Aust J Forensic Sci 24:1–2. https://doi.org/10.1080/00450618.2018.1474947
24. Kazmi S, Mânica S, Revie G, Shepherd S, Hector M (2019) Age estimation using canine pulp volumes in adults: a CBCT image analysis. Int J Legal Med 133(6):1967–1976. https://doi.org/10.1007/s00414-019-02147-5
25. Molina A, Bravo M, Fonseca GM, Márquez-Grant N, Martín-de-Las-Heras S (2021) Dental age estimation based on pulp chamber/crown volume ratio measured on CBCT images in a Spanish population. Int J Legal Med 135(1):359–364. https://doi.org/10.1007/s00414-020-02377-y