

Standardization and Evaluation of Mandibular Osteometric Parameters on Panoramic Radiographs for Forensic Age Estimation in South Indian Population: Development of a Prototype Digital Application Tool

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Abstract

Introduction

Mandibular morphometric parameters measured on panoramic radiographs have been widely investigated for forensic age and sex estimation because they exhibit age- and sex-related anatomical variations. However, evidence regarding their predictive value in South Indian populations remains limited. This study evaluated the reliability and forensic applicability of selected mandibular morphometric parameters for age and sex estimation in a South Indian population.

Materials & Methods

A retrospective radiographic study was conducted on 600 panoramic radiographs of individuals aged 3–88 years retrieved from departmental archives. Participants were stratified into nine age groups. Six mandibular morphometric parameters—antegonial angle, antegonial depth, condylar height, coronoid height, superior mental foramen distance, and inferior mental foramen distance—were measured using standardized digital protocols. Multiple linear regression analysis was performed to develop an age prediction model, while independent t-tests were used to assess sex-related differences. Statistical significance was set at $p < 0.05$.

Results

All mandibular parameters demonstrated significant age-related variations ($p < 0.05$). Antegonial angle exhibited a significant negative association with age ($B = -0.104$, $p < 0.001$), and inferior mental foramen distance also decreased significantly with advancing age ($B = -0.061$, $p < 0.001$). Condylar and coronoid heights increased until early adulthood and subsequently declined with age. Males showed significantly greater condylar height, coronoid height, and antegonial angle than females ($p < 0.05$). The regression model demonstrated moderate predictive performance for age estimation ($R^2 = 0.36$).

Conclusion

Mandibular morphometric parameters, particularly antegonial angle, coronoid height, and mental foramen-related distances, may serve as useful adjunctive indicators for forensic age and sex estimation. Although the proposed regression model provides moderate predictive accuracy, panoramic radiographic limitations preclude their use as standalone forensic markers. Further multicenter validation across diverse populations is warranted to improve generalizability and predictive performance.

Clinical Trial Registration

Introduction

Accurate estimation of age and sex from skeletal remains is essential in forensic identification, particularly in severely damaged bodies where conventional methods such as fingerprint analysis and DNA profiling are challenging [1]. The skull, along with the pelvis, serves as one of the most reliable indicators for determination of age and sex. In cases where the skull is completely fragmented, the mandible and its anatomical features become the preferred choice for personal identification [2][3]. The mandible is recognized as one of the most resilient and sexually dimorphic bone within the skull, with a notable ability to withstand post-mortem changes [4][5]. Mandibular shape and orientation are influenced by masticatory muscle attachments and their functions, especially the temporalis and masseter, leading to variations in the condylar and coronoid processes. Genetic and hormonal factors also contribute to morphological differences in the sigmoid notch [6].

Dental age estimation is primarily based on radiographic evaluation of teeth and its related structures, providing a reliable indicator of skeletal development with minimal environmental influences. Panoramic radiography is widely used to assess dental maturation stages in children and adolescents aiding in accurate age determination for forensic and clinical purposes [7][8]. Since its introduction in 1950, it has become the most widely used extraoral imaging modality, offering a comprehensive visualization of the maxillofacial structures in a single radiograph [9][10]. It is valued for its non-invasive nature, rapid acquisition, high reproducibility, cost-effectiveness, minimizing patient exposure to ionizing radiation [11][12].

Mandibular measurements are commonly used for estimating both age and gender in unidentified individuals, as the mandible shows distinct sexual dimorphism in its dimensions, morphology, angulation, and degree of flaring. Loth et al, reported significant gender differences in mandibular angulation, supporting its forensic value in identification [13][14]. Various other morphometric parameters including inter-coronoid distance, bicondylar breadth, vertical and horizontal dimensions measured on panoramic radiographs are useful in forensic assessment. In addition, the position of the mandibular foramen relative to the mandibular borders serves as an additional indicator for sex determination [15][16].

The present study selected six specific mandibular morphometric parameters such as antegonial angle, antegonial depth, condylar height, coronoid height, and the vertical distances from the superior and inferior borders of the mental foramen to the inferior border of the ramus as they reflect key vertical, angular, and spatial changes in mandibular morphology associated with growth and functional remodeling[17]. These parameters were chosen based on their reproducibility on panoramic radiographs, ease of measurement, and documented relevance in previous morphometric and anthropological studies [13–17]. In contrast to earlier research that has largely evaluated these measurements individually or primarily for sex determination, the present study integrates all six parameters into a unified model

specifically aimed at age estimation. It also addresses the existing gap in population-specific evidence by focusing on a South Indian study sample. Importantly, this study extends beyond conventional morphometric analysis by translating the findings into a prototype digital application tool, enabling practical utility in future.

The primary aim of this study was to evaluate the usefulness of selected mandibular morphometric parameters for age estimation using panoramic radiographs in a south Indian population and to determine their reliability as indicators for forensic identification and anthropological applications.

The secondary aims were to assess the sex-related variations in these mandibular parameters and to propose a prototype chairside digital application for mobile and computer platforms based on the study findings. The proposed application represents a preliminary step towards translating the obtained morphometric data into a practical digital format for future forensic and clinical use.

This study was based on the hypothesis that mandibular morphometric parameters exhibit significant age-related changes and can serve as reliable indicators for age estimation. It was further hypothesized that these parameters demonstrate sex-specific variations and may potentially be incorporated into a digital platform for future age assessment applications.

Materials and methods

This retrospective, radiographic study was conducted in the premises of Saveetha Dental college affiliated to Saveetha Institute of Medical and Technical Sciences (SIMATS), Chennai, India. The study commenced after approval from the Research board of the university (SRB/SDC/OPATH-2404/24/514). As this was a retrospective design, all eligible panoramic radiographs archived in the Department of Oral Medicine and Radiology during the study period were included, resulting in a total sample size of 600 subjects. To assess the sample adequacy, a post hoc power analysis was performed and the analysis confirmed that the sample size was adequate to detect statistically significant associations between mandibular morphometric parameters and age. The details of the power analysis are presented in Table 1.

Table 1
Post hoc power analysis of the multiple regression model based on sample size, number of predictors, effect size (R^2), and significance level (α).

PARAMETER	VALUE
Statistical Test	Post hoc: Compute Achieved Power
Distribution	Exact Distribution
Tail(s)	One-tailed
H1 ρ^2	0.3528433
H0 ρ^2	0
α Error Probability	0.05
Total Sample Size	600
Number of Predictors	7
Lower Critical R^2	0.0233847
Higher Critical R^2	0.0233847
Achieved Power ($1 - \beta$ Error Probability)	1.0000000

The study sample comprised individuals in age from 4 to 85 years old. To systematically analyze the data, the X-rays were sorted into nine different age categories (0–10, 10–20, 20–30, and so on, up to 80–90 years). The distribution of subjects across these age groups was unequal due to the retrospective design of the study. Since all eligible panoramic radiographs available during the study period were included, the sample distribution depended on the availability of suitable clinical records rather than predetermined age stratified recruitment. However, all age groups were adequately represented to permit statistical analysis and comparison. The specific breakdown of how many samples fell into each group can be found in Table 2.

Table 2
Age-wise distribution of the study population
according to sample size

S. NO	AGE GROUP	NUMBER OF SAMPLES
1.	0–10	100
2.	10–20	100
3.	20–30	100
4.	30–40	50
5.	40–50	50
6.	50–60	50
7.	60–70	50
8.	70–80	50
9.	80–90	50

Inclusion and Exclusion Criteria

The selection criteria consisted of panoramic radiographs obtained between 2019 and 2020 from the archives of the radiology department originally acquired for diagnostic purposes unrelated to the present research. Only radiographs of high quality characterized by optimal angulation, appropriate contrast, standardized head positioning and adequate resolution to minimize distortion were considered. Additionally, the selected images were required to be free of artifacts and to clearly define intact anatomical landmarks including the antegonial angle, antegonial depth, mental foramen and the mandibular ramus region.

Reliable measurements require high-quality images so strict exclusion criteria were followed. Any radiographs that failed to clearly show the dental arch, the mental foramen or the inferior border of the mandible were removed. Images with distortion or significant asymmetry were also excluded. In addition, cases with a history of mandibular pathologies like ameloblastoma or squamous cell carcinoma were also not included. By using only images obtained via standardized imaging protocols the overall consistency of the data was ensured.

Standardization Criteria

Image Acquisition Protocol:

Panoramic radiographs were acquired following a standardized protocol with the mandible positioned protrusively using a bite block to ensure proper alignment. Teeth were maintained in centric occlusion

during imaging and the lips were kept relaxed to minimize soft tissue superimposition and reduce the shadowing effects [18].

Patient Positioning Standards & Radiation Dosage:

The head was positioned in the Natural Head Position (NHP) ensuring that the mid sagittal plane and canine guidance line were properly aligned with the Frankfort horizontal plane maintained parallel to the floor as per established reference standards. All radiographic images were processed under controlled, standardized digital conditions. The radiation dose from the orthopantomogram (OPG) was approximately 0.014 mSv representing a low dose that is considered safe for patients [19].

Measurement Protocol:

Radiographic anatomical landmarks used for assessing mandibular indices were identified and traced digitally on the panoramic radiographs. The analysis was performed using Adobe Photoshop version 2020 with all the linear measurements recorded in millimeters and angular measurements in degrees applying precise digital scaling to ensure accuracy. This method enabled detailed morphometric evaluation which was crucial for the study outcomes. All measurements were performed independently by two examiners. To assess intra-observer reliability, a subset of radiographs was randomly selected and re-evaluated by the same examiner after a two-week interval under identical conditions. Inter-observer reliability was assessed independently by the second examiner using the same measurement protocol. Agreement between measurements was evaluated using the intraclass correlation coefficient (ICC), and statistical significance was assessed and the results are tabulated in [Table 3]. All morphometric measurement method used in this study is based on previously validated techniques reported in the literature, ensuring methodological accuracy, reliability and reproducibility [17].

Table 3
Intra-observer agreement analysis for
mandibular osteometric parameters showing
p values and agreement coefficients for
repeated measurements

Antegonial angle	p value	Agreement
	0.654	0.981
Antegonial depth	1.00	0.88
Condylar height	0.796	0.998
Coronoid height	0.796	0.998
Superior border	0.605	0.978
Inferior border	0.693	0.969

Radiographic analysis was performed by a trained and calibrated examiner with expertise in oral and maxillofacial pathology and forensic odontology. All measurements were carried out under standardized conditions in accordance with established measurement protocols.

The following six mandibular morphometric parameters were measured digitally:

Antegonial Angle

Two lines were drawn intersecting at the point of maximum depth along the inferior border of the mandible. The first line extends along the anterior portion of the inferior border of the mandible, while the second passes through the inferior border at the gonion [Figs. 1] [20].

Antegonial Depth

The height difference between the deepest point of the mandible and its inferior border was measured [Figs. 2] [20].

Condylar height

The linear distance was measured between the most superior point of the condyle and the most inferior point of the inferior border of the body of the mandible [Figs. 3] [21].

Coronoid height

The linear distance was measured among the most superior points of the coronoid process and the most inferior point of the inferior border of the body of the mandible [Figs. 4] [22].

The length measured between the superior margin of the mental foramen and the inferior border of the ramus of the mandible was recorded for analysis [Figs. 5] [23]. The distance measured between the inferior margin of the mental foramen and the inferior border of the ramus of the mandible was recorded for analysis [Figs. 6] [24]. The statistical analysis was performed using Stata Version 18. Descriptive statistics were calculated for all mandibular morphometric parameters and are presented as mean $\pm$ standard deviation. Age-stratified analyses were performed to evaluate variations in mandibular measurements across different age groups. Multiple linear regression analysis was performed to evaluate the association between age (dependent variable) and the selected mandibular morphometric parameters, namely antegonial angle, antegonial depth, condylar height, coronoid height, superior border distance, and inferior border distance (independent variables). Prior to analysis, the assumptions of linear regression, including linearity, normality, and independence of observations, were assessed. Regression coefficients (β), 95% confidence intervals (CI), and p values were calculated for each predictor variable. A p value of < 0.05 was considered statistically significant. The coefficient of determination (R^2) was used to evaluate the explanatory ability of the regression model.

Development of a Prototype Digital Chairside Age Estimation Tool: Smart ImAGE G

Using the osteometric parameters derived from panoramic radiographs, a prototype digital application, Smart ImAGE G, was developed for age estimation. The application was designed to function on both mobile and desktop platforms, enabling manual input of mandibular morphometric measurements. In addition, it also incorporates tools for performing linear and angular measurements directly on uploaded orthopantomograms (OPGs), along with basic image enhancement features to improve visualization of anatomical landmarks [Fig. 7]. The platform facilitates standardized data entry, secure storage, and export of recorded measurements for further analysis and documentation. Demographic variables, including sex and age group categories, were also incorporated to support stratified evaluation. The prototype was developed as an initial framework for the future incorporation of regression-based age estimation models. The patent for the application has been published, and the tool is intended to serve as a decision-support aid, rather than replacing expert interpretation.

Results

The morphometric analysis of the mandible included measurement of parameters such as the Antegonial Angle (AA), Antegonial Depth (AGD), Condylar Height (CH), Coronoid Height (CrH), and the height difference between the superior and inferior borders of the mental foramen. These measurements were systematically evaluated and tabulated for further analysis.

A total of 600 panoramic radiographs were included in the study, with participant ages ranging from 3 to 88 years (mean age: 38.03 ± 25.61 years). The post hoc power analysis for the multiple regression model demonstrated an achieved power of 1.00 at an α level of 0.05, indicating adequate statistical power for the study design and the results are tabulated in Table 1.

Descriptive analysis [Table 4] demonstrated variability in all evaluated mandibular morphometric parameters. Among the assessed variables, condylar height and coronoid height exhibited comparatively higher mean values, whereas antegonial depth showed lower mean measurements with wider inter-individual variation. These findings suggest considerable anatomical diversity within the study population.

Table 4

Descriptive statistics of age and mandibular osteometric parameters including minimum, maximum, mean, and standard deviation values of the study population Values are presented as Mean $\pm$ Standard Deviation (SD)

PARAMETER	N	MINIMUM	MAXIMUM	MEAN	STANDARD DEVIATION
Age	600	3	88	38.03	25.616
Antegonial Angle	600	121.9	178.4	145.492	9.4986
Antegonial Depth	600	0.56	37.66	1.52	1.64
Condylar height	599	30.44	68.51	47.21	6.91
Coronoid height	600	29.63	61.15	43.82	6.46
Superior border From mental foramen	600	1.19	32.74	8.10	2.30
Inferior border frommental foramen	600	2.80	42.05	6.84	2.25

Table 5 Age-wise distribution of mandibular osteometric parameters expressed as mean $\pm$ standard deviation across different age groups

Age Group	Antegonial Angle (°)	Antegonial Depth (mm)	Condylar Height (mm)	Coronoid Height (mm)	Superior Border (mm)	Inferior Border (mm)
0–10 yrs	156.90 ± 11.31	1.45 ± 3.66	40.12 ± 3.44	42.34 ± 3.46	6.39 ± 1.55	5.94 ± 3.93
11–20 yrs	141.82 ± 5.26	1.20 ± 0.31	47.00 ± 3.75	50.16 ± 4.09	9.09 ± 1.41	8.04 ± 1.39
21–30 yrs	143.44 ± 6.40	1.26 ± 0.14	49.44 ± 4.13	53.60 ± 4.61	9.45 ± 1.34	8.25 ± 1.08
31–40 yrs	147.82 ± 6.18	1.37 ± 0.15	49.93 ± 4.66	53.76 ± 4.90	9.93 ± 0.81	8.41 ± 0.78
41–50 yrs	148.09 ± 6.72	1.87 ± 2.14	47.93 ± 4.09	51.63 ± 4.31	8.29 ± 1.01	6.95 ± 1.01
51–60 yrs	148.06 ± 5.64	1.59 ± 0.16	44.13 ± 4.20	47.47 ± 2.91	7.75 ± 0.85	6.16 ± 0.96
61–70 yrs	144.92 ± 4.49	1.68 ± 0.18	41.11 ± 2.61	44.85 ± 2.77	7.52 ± 1.03	6.12 ± 1.03
71–80 yrs	140.48 ± 4.81	1.85 ± 0.22	36.88 ± 3.67	41.39 ± 3.61	6.42 ± 1.15	4.74 ± 0.89
> 80 yrs	132.40 ± 4.76	2.04 ± 0.21	33.15 ± 1.73	35.07 ± 1.83	7.41 ± 5.26	5.31 ± 0.92

Values are presented as Mean ± Standard Deviation (SD)

Age-wise assessment [Table 5] revealed characteristic trends in mandibular morphology. Condylar and coronoid heights increased progressively from childhood and reached peak values during early adulthood, followed by a gradual decline in older age groups. In contrast, antegonial depth demonstrated a gradual increase with advancing age. Measurements related to the mental foramen showed relatively higher values in younger adults with mild reduction in elderly individuals. These findings indicate age-associated remodelling changes within the mandible and support the utility of mandibular morphometric parameters as potential indicators for forensic age estimation and anthropological assessment.

Multiple linear regression analysis [Table 6] demonstrated that several mandibular parameters were significantly associated with chronological age. Antegonial angle showed a significant negative association with age ($B = -0.99$, $p < 0.001$; 95% CI: -1.17 to -0.80), indicating progressive reduction in angle values with advancing age. Similarly, coronoid height ($B = -0.60$, $p < 0.001$; 95% CI: -0.85 to -0.36) and inferior border distance from the mental foramen ($B = -0.57$, $p < 0.001$; 95% CI: -0.82 to -0.32) demonstrated significant inverse relationships with age. Antegonial depth exhibited a positive association with age ($B = 0.36$, $p = 0.016$; 95% CI: 0.07–0.65), while condylar height also showed a statistically significant association ($B = 0.29$, $p = 0.013$; 95% CI: 0.06–0.51). The superior border distance from the mental foramen was not significantly associated with age ($p = 0.633$).

Table 6
Regression analysis of mandibular osteometric parameters showing regression coefficients (B), t values, and significance levels

STUDY PARAMETER	B	T	SIGNIFICANCE
AGA	– .104	-10.844	.000
AGD	.034	2.454	.014
SB	.015	1.225	.221
IB	– .061	-4.795	.000

ABBREVIATIONS: Antegonial Angle (AGA), Antegonial Depth (AGD), Superior (SB) and Inferior borders (IB) of the mental foramen to the inferior border of the mandibular ramus

The regression model [Table 7] demonstrated a moderate predictive strength for age estimation with an R^2 value of 0.36, indicating that approximately 36% of the variation in chronological age could be explained by the evaluated mandibular parameters. Among the studied variables, antegonial angle, coronoid height, and inferior border distance from the mental foramen emerged as the most clinically relevant indicators for age estimation due to their stronger statistical associations. These parameters may therefore serve as supportive adjunctive markers in forensic identification, age profiling, anthropological investigations, and medico-legal assessments, particularly in situations where skeletal remains are fragmented or when other age estimation methods are unavailable. Furthermore, morphometric evaluation of the condylar and coronoid regions may also have clinical relevance in maxillofacial surgery, prosthodontic rehabilitation, implant planning, and assessment of mandibular growth-related changes.

Table 7
Multiple linear regression analysis of mandibular osteometric parameters for age estimation showing regression coefficients, p-values, 95% confidence intervals, and model fit (R^2)

Variable	Regression Coefficient (B)	p-value	95% Confidence Interval
Antegonial angle	-0.99	< 0.001	-1.17 - -0.8
Antegonial depth	0.36	0.016	0.07–0.65
Condylar height	0.29	0.013	0.06–0.51
Coronoid height	-0.6	< 0.001	-0.85 - -0.36
Superior border	0.07	0.633	-0.22–0.36
Inferior border	-0.57	< 0.001	-0.82 - -0.32
Intercept	240.79	< 0.001	212.3–269.29
R^2	0.36		

Table 8 Comparison of mandibular osteometric parameters between males and females showing mean values and statistical significance.

Study Parameter	Gender	N	Mean	SIGNIFICANCE
Ante gonial Angle	Male	302	145.812	0.015*
	Female	298	145.168	
Ante gonial Depth	Male	302	1.52	0.569
	Female	298	1.52	
Condylar Height	Male	301	47.57	0.000*
	Female	298	46.86	
Coronoid Height	Male	302	44.37	0.000*
	Female	298	44.32	
Superior Border from mental foramen	Male	302	8.1	0.017*
	Female	298	8.08	
Inferior Border From mental Foramen	Male	302	6.82	0.024*
	Female	298	6.86	
Independent T test * P value less than or equal to 0.05 is considered statistically significant difference				

Sex-based comparison [Table 8] revealed significant sexual dimorphism in several mandibular measurements. Males exhibited significantly greater antegonial angle, condylar height, and coronoid height values compared to females ($p < 0.05$). Significant sex-related differences were also observed in measurements associated with the mental foramen. However, antegonial depth did not demonstrate a statistically significant sex difference. These observations further support the applicability of mandibular morphometric analysis in sex estimation and population-based forensic investigations.

Based on the obtained morphometric findings, a prototype digital chairside application, Smart ImAGE G, was developed to facilitate standardized measurement recording and future integration of regression-based age estimation models. The current prototype supports manual measurement entry, image visualization, and data storage functions. The proposed platform may aid clinicians and forensic experts in rapid morphometric documentation and improve standardization during radiographic analysis. However, external validation and prospective clinical testing of the application have not yet been performed, and the tool should presently be considered a preliminary decision-support framework rather than a validated automated age estimation system.

Discussion

The present study evaluated mandibular morphometric parameters derived from panoramic radiographs for age and sex estimation in a South Indian population. The results demonstrated that multiple mandibular indices such as antegonial angle, antegonial depth, condylar height, coronoid height and distance from superior and inferior border of mental foramen to the inferior border of the ramus of the mandible shows statistically significant associations with chronological age and sex, highlighting the use of mandibular morphology as a supportive tool in forensic identification. Bivariate regression analysis showed significant age correlations: AGA decreased with advancing age ($B = -0.104$, $p < 0.001$), while AGD ($B = 0.034$, $p = 0.014$) increased. The observed age-related variations in mandibular parameters can be explained by continuous skeletal remodeling throughout life. During growth and early adulthood, condylar and coronoid regions show progressive increase due to active bone formation and functional adaptation related to masticatory activity. The peak values observed in early adulthood reflect maximal skeletal maturity. Thereafter, the gradual decline seen in older age groups is attributed to age-related bone resorption, reduced masticatory muscle activity, and degenerative changes in the temporomandibular joint. Similarly, the antegonial region reflects remodeling influenced by muscle pull and cortical bone resorption, explaining the progressive reduction in antegonial angle with age. Changes in the position of the mental foramen observed in this study are also consistent with long-term mandibular remodeling. The relative vertical shift of the foramen with age may be due to the alveolar bone loss, mandibular basal resorption, and continued skeletal adaptation. These findings support the concept that the mental foramen is not a completely stable landmark throughout life, particularly when wide age ranges are considered.

Rad et al investigated several mandibular parameters in an Iranian population and found significant differences between males and females for all measured features, including the gonial angle. The study identified coronoid height, bicondylar width, and ramus height as the most reliable indicators for gender determination. The findings underscore the significance of specific mandibular measurements in forensic gender identification [25]. Ulusoy and Ozkara et al identified several mandibular variables, including condylar height, coronoid height, ramus widths, bigonial and bicondylar breadths, and mental foramen height, as significantly differing between males and females. However, their univariate analysis showed that the gonial angle was the only parameter that did not exhibit significant gender differences [26].

Dutra et al reported that males exhibited significantly smaller antegonial angles ($160.86^\circ \pm 0.78$) compared to females ($165.08^\circ \pm 0.58$), regardless of dental status ($p < 0.0001$). It was also noted that edentulous individuals had smaller antegonial angles than those who were dentate or partially dentate ($p < 0.05$) [27]. Similarly, Ghosh et al found no statistically significant change in antegonial angle with age for either sex, though a slight trend was observed [28].

The significant gender differences observed in mandibular parameters in the present study align with the existing literature that underscores pronounced sexual dimorphism in mandibular morphology. The

findings from the study that males in the South Indian population sample had slightly larger antegonial angles (145.81°) than females (145.17°) are in contrast with the research by Dutra et al., who reported that males in their study population exhibited significantly smaller antegonial angles than females. This indicates that the patterns of sexual dimorphism in mandibular morphology can vary among different populations and highlights the necessity of establishing distinct forensic standards for different ethnic groups. Additionally, distances from both the superior and inferior borders of the mental foramen varied significantly between sexes, while antegonial depth showed no gender-related difference. These morphometric indices strengthen the role of mandibular measurements as reliable indicators for age and gender determination in both clinical practice and forensic investigations. According to Esfehiani et al, condylar height emerged as the most reliable indicator for gender differentiation, demonstrating 87% accuracy with high sensitivity and specificity. Males exhibited significantly greater condylar heights compared to females, corroborating findings from prior research. A threshold of 66.72 mm was identified, above which the gender is likely male. Coronoid height was the second most reliable marker, with an accuracy of 82.65% and similarly strong diagnostic performance, aligning with earlier studies [17].

The findings of the study established significant variations in age-related changes; for instance, the condylar height increased from childhood (mean 40.12 mm), peaked during early adulthood (49.93 mm in ages 31–40), and gradually declined to 33.15 mm in the elderly (81–90 years) due to degenerative processes and bone loss. Similarly, the coronoid height exhibited a similar trajectory, peaking at 53.76 mm in early adulthood and decreasing to 35.07 mm in advanced age. The decline in these measurements suggest that age-related remodeling and reduced masticatory function contribute to structural changes in the mandible and temporomandibular joint. Collectively, these findings highlight the dynamic nature of mandibular growth and degeneration making both condylar and coronoid heights as key indicators of developmental and aging-related morphological changes in forensic and clinical assessments.

Previous studies revealed the vertical position of the mental foramen relative to the inferior border of the mandible was evaluated for its potential in gender determination. Univariate analysis revealed that the distances from both the inferior and superior borders to the mental foramen could predict gender with probabilities of 75% and 78%, respectively. While this parameter demonstrated high specificity, it exhibited lower sensitivity, making it more effective in identifying females than males. The current findings confirm the findings of previous studies [28–31].

The results showed significant age-related variation in the distance from the superior border of the mental foramen, which was smallest in children (6.39 mm), peaked in adults aged 31–40 years (9.93 mm), and declined gradually in older groups. Similarly, the distance from the inferior border of the mandible to the mental foramen demonstrated a significant change with age, ranging from 8.41 mm in adults aged 31–40 years to 4.74 mm in the 71–80 years group. From a methodological perspective, panoramic radiography, while widely used, is associated with inherent limitations such as magnification, geometric distortion, and patient positioning errors. The relatively strong reproducibility of mandibular

landmarks such as condylar and coronoid height supports their suitability for morphometric analysis in forensic applications. These limitations may influence linear and angular measurements, particularly in posterior mandibular regions. Although standardized imaging protocols and consistent landmark identification were used to minimize variability, residual measurement error and inter-observer variability cannot be excluded. In particular, landmark-dependent structures such as mental foramen position may exhibit greater susceptibility to observer bias compared to more stable landmarks such as condylar and coronoid height. These factors highlight the importance of calibration and reproducibility testing in morphometric forensic studies.

The moderate predictive strength of the regression model ($R^2 = 0.36$) indicates that mandibular parameters alone cannot fully account for chronological age variation. This is expected, as age estimation is a multifactorial process influenced by genetic, environmental, and functional factors. Nevertheless, the significant associations observed for antegonial angle, coronoid height, and inferior border–mental foramen distance suggest that these parameters may serve as reliable adjunctive markers rather than standalone predictors.

The development of the prototype digital application tool, Smart ImAGE G, represents an effort to translate mandibular morphometric findings into a structured and clinically applicable forensic support tool. In comparison to existing AI-based forensic models such as convolutional neural networks (CNN), artificial neural networks (ANN), Bayesian CNN, and hybrid HCNN–KNN systems for age and sex estimation from maxillofacial radiographs, the present tool is designed primarily to standardize data entry, enhance measurement consistency, and reduce observer-related variability [32].

However, unlike fully AI-driven systems reported in the literature, Smart ImAGE G currently functions as a support tool and does not incorporate automated machine learning–based prediction algorithms. Therefore, it should not be interpreted as an autonomous diagnostic system. The current prototype also has several limitations, including the absence of external validation on multicentric and ethnically diverse datasets, limited generalizability, and reliance on manual landmark identification, which may still introduce operator-dependent bias.

Previous AI-based studies have highlighted that robust forensic prediction models requiring larger datasets, rigorous training and testing protocols, and population-specific bias prior to clinical or medico-legal application. Moreover, forensic implementations demand high levels of interpretability, reproducibility, and validation across multiple imaging modalities and populations [32].

Hence, Smart ImAGE G should presently be regarded as a preliminary assistive research tool rather than a definitive AI-based forensic diagnostic system. Future development is intended to focus on integrating validated AI algorithms, automated landmark detection, multicentric radiographic datasets, and explainable AI frameworks to enhance predictive reliability and forensic applicability.

Limitations:

It is acknowledged that panoramic radiographs are associated with inherent limitations, including distortion, magnification errors, and superimposition of anatomical structures, which may affect measurement accuracy. In addition, the retrospective study design may introduce certain limitations, such as selection bias and limited control over image acquisition parameters. Although panoramic radiography offers a practical and widely accessible imaging modality for forensic assessment, advanced imaging techniques such as Cone-Beam Computed Tomography (CBCT) provide three-dimensional visualization and may allow more precise and reliable morphometric measurements.

Conclusion

This study demonstrated dynamic remodeling changes in the antegonial region influenced by age, sex, and dental status. Selected mandibular morphometric parameters showed measurable age- and sex-related variations on panoramic radiographs and may serve as supportive indicators for forensic age estimation within the studied population. Among the evaluated measurements, the antegonial angle, coronoid height, and inferior border distance from the mental foramen emerged as the most reliable mandibular parameters for forensic age estimation due to their stronger association with chronological age. These parameters may therefore serve as adjunctive indicators in forensic identification and anthropological assessment. Although panoramic radiography is a practical and accessible imaging modality, limitations such as image distortion, magnification errors, and the retrospective study design should be considered while interpreting the findings. Therefore, the results cannot be generalized beyond the studied population. A prototype digital chairside application, Smart ImAGE G, was developed for standardized morphometric recording and future integration of age estimation models. However, the application has not undergone external validation or prospective clinical testing and should presently be considered a preliminary decision-support tool. Further multicentric studies using larger datasets and three-dimensional imaging modalities such as Cone-Beam Computed Tomography (CBCT) are required to validate and refine the proposed approach.

Abbreviations

OPG Orthopantomogram

Antegonial Angle (AGA): Angle formed between the intersection of two lines at the deepest point of inferior border of mandible. The first line passes through anterior part of inferior border

Antegonial Depth (AGD): Vertical distance between inferior border of mandible to its deepest point

Condylar Height (CH): Distance between the superior most part of the condyle and the inferior part of inferior border of the mandible

Coronoid Height (CrH): Distance between the superior part of the coronoid process and the most inferior part of inferior border of the mandible

Distances from the superior and inferior borders of the mental foramen to the inferior border of the mandibular ramus.

Declarations

Human Ethics and Consent to Participate

This study was reviewed and approved by the Institutional Human Ethics Committee of Saveetha Dental College and Hospitals, affiliated with Saveetha Institute of Medical and Technical Sciences (SIMATS), Chennai, India (Approval Number (SRB/SDC/OPATH-2404/24/514). The study was conducted in accordance with the ethical principles of the Declaration of Helsinki and its subsequent amendments. As this was a retrospective study using archived panoramic radiographs with anonymized patient data, the requirement for informed consent was waived by the Institutional Ethics Committee.

Consent to participate

The requirement for informed consent was waived by the Institutional Human Ethics Committee because this was a retrospective study using anonymized archived panoramic radiographs

Clinical Trial Registration: Not applicable

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Author Contributions

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Competing interests

The authors declare no competing interests

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Figures

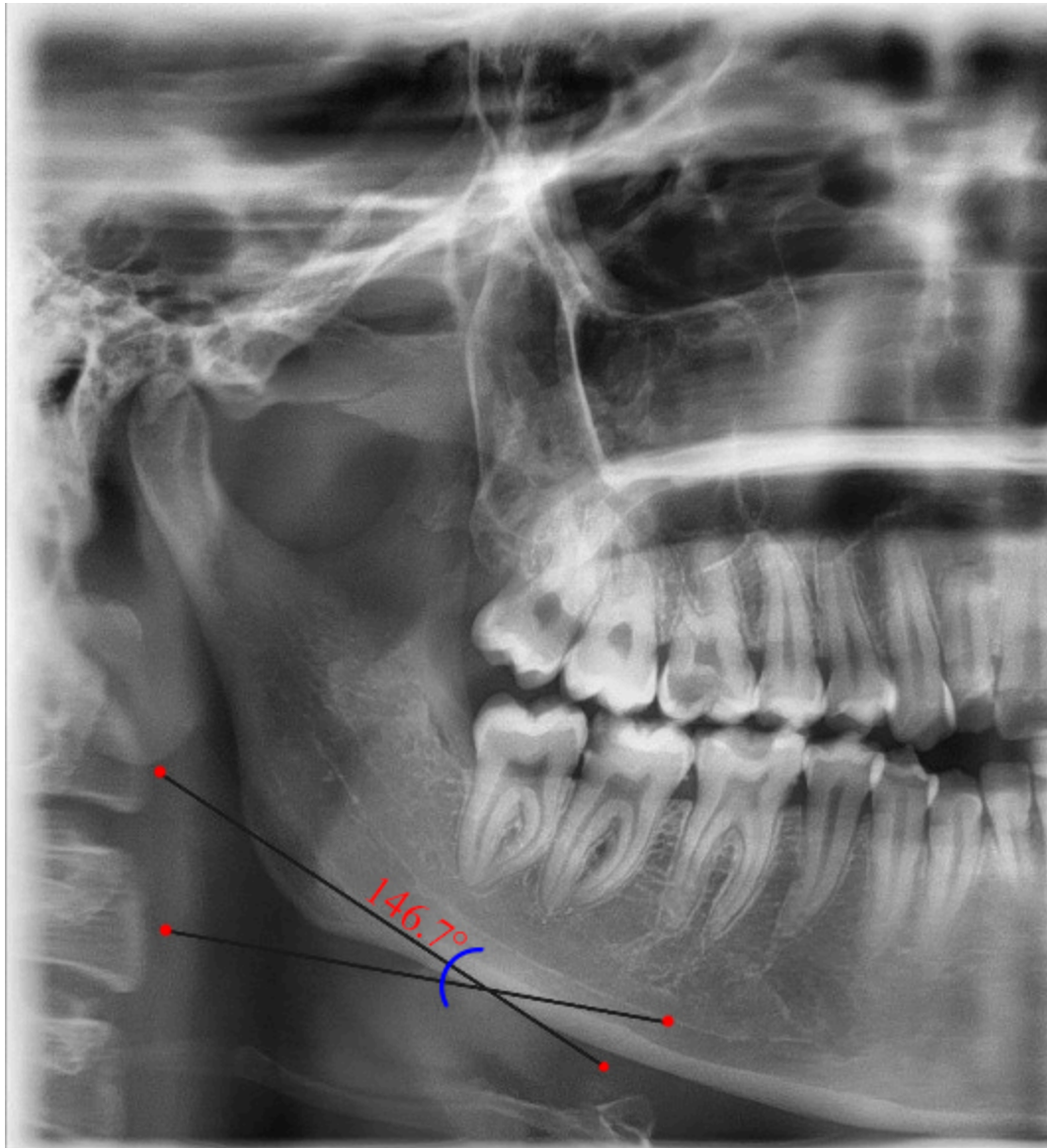


Figure 1

Measurement of the antegonial angle (in degrees) on OPG

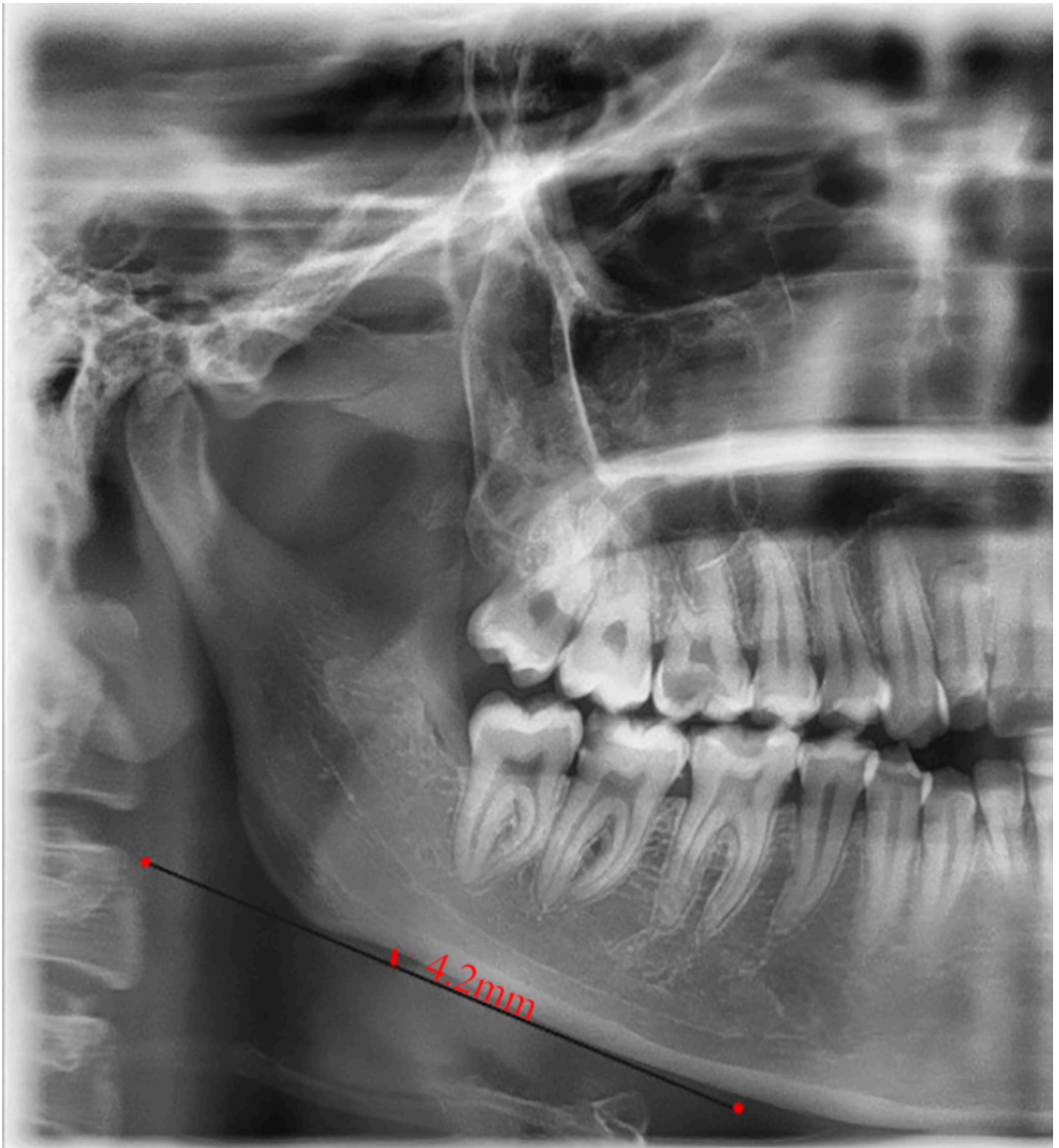


Figure 2

Measurement of Antegonial Depth (millimeters) on OPG

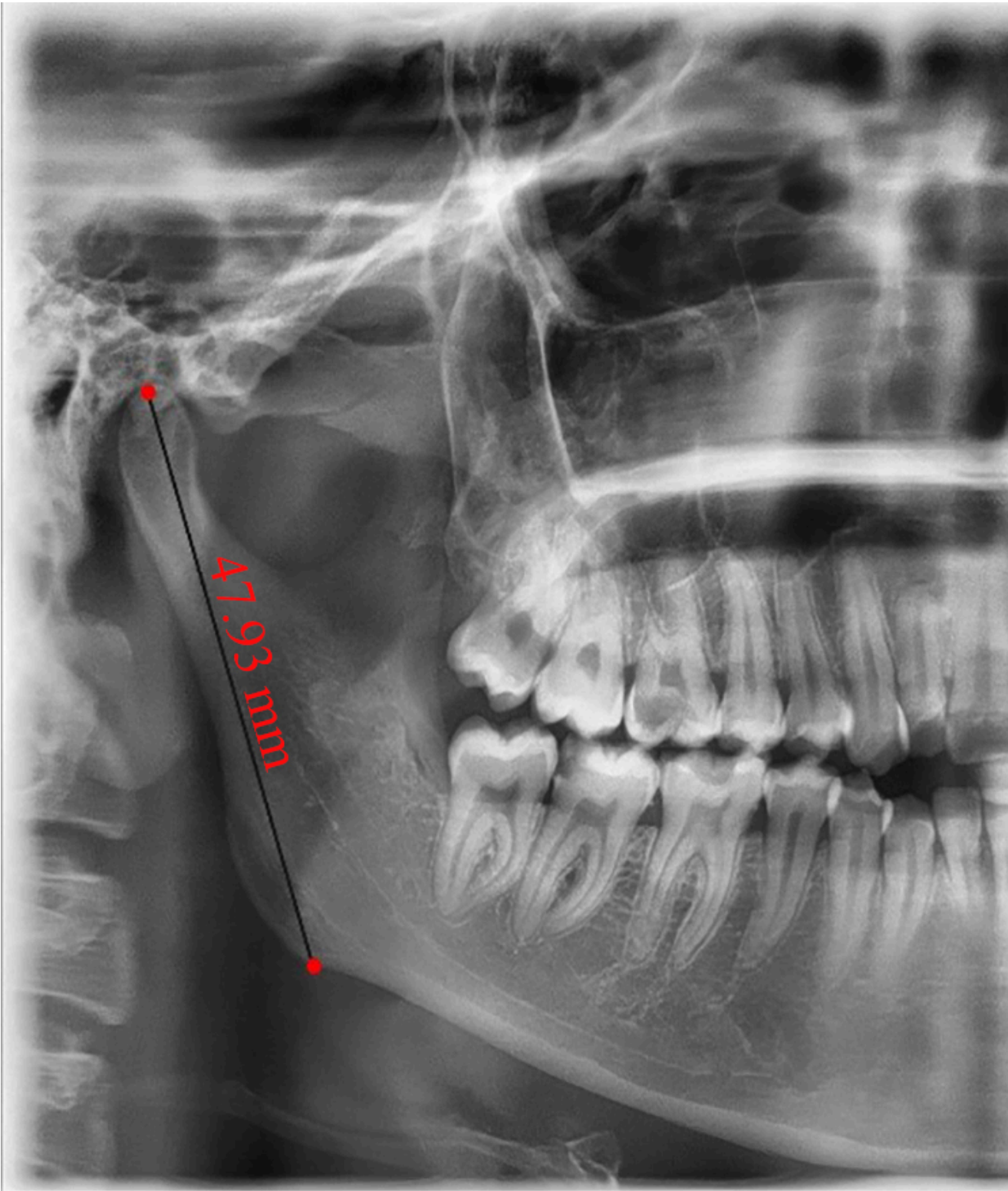


Figure 3

Measurement of Condylar Height (millimeters) on OPG

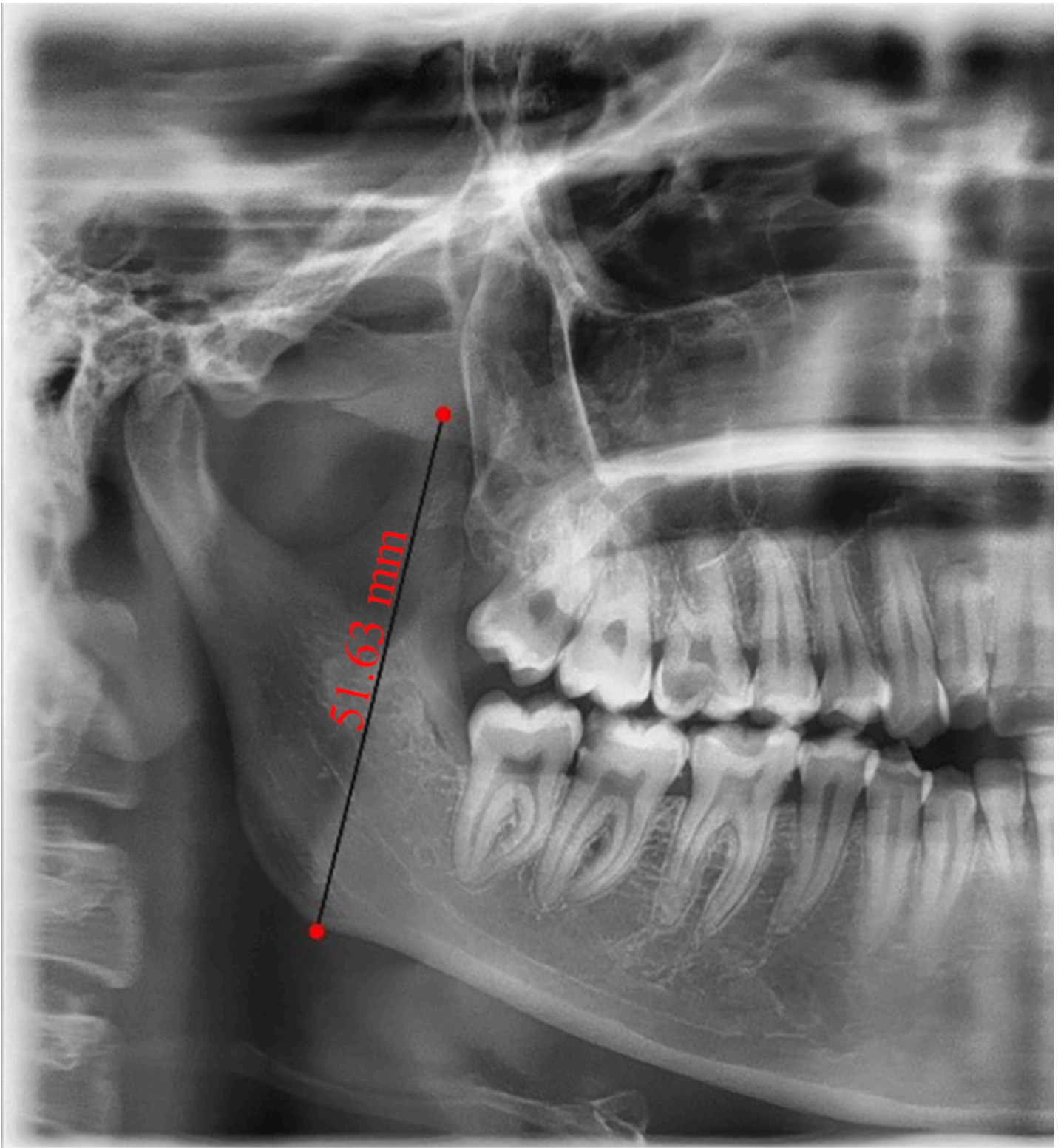


Figure 4

Measurement of Coronoid Height (millimeters) on OPG

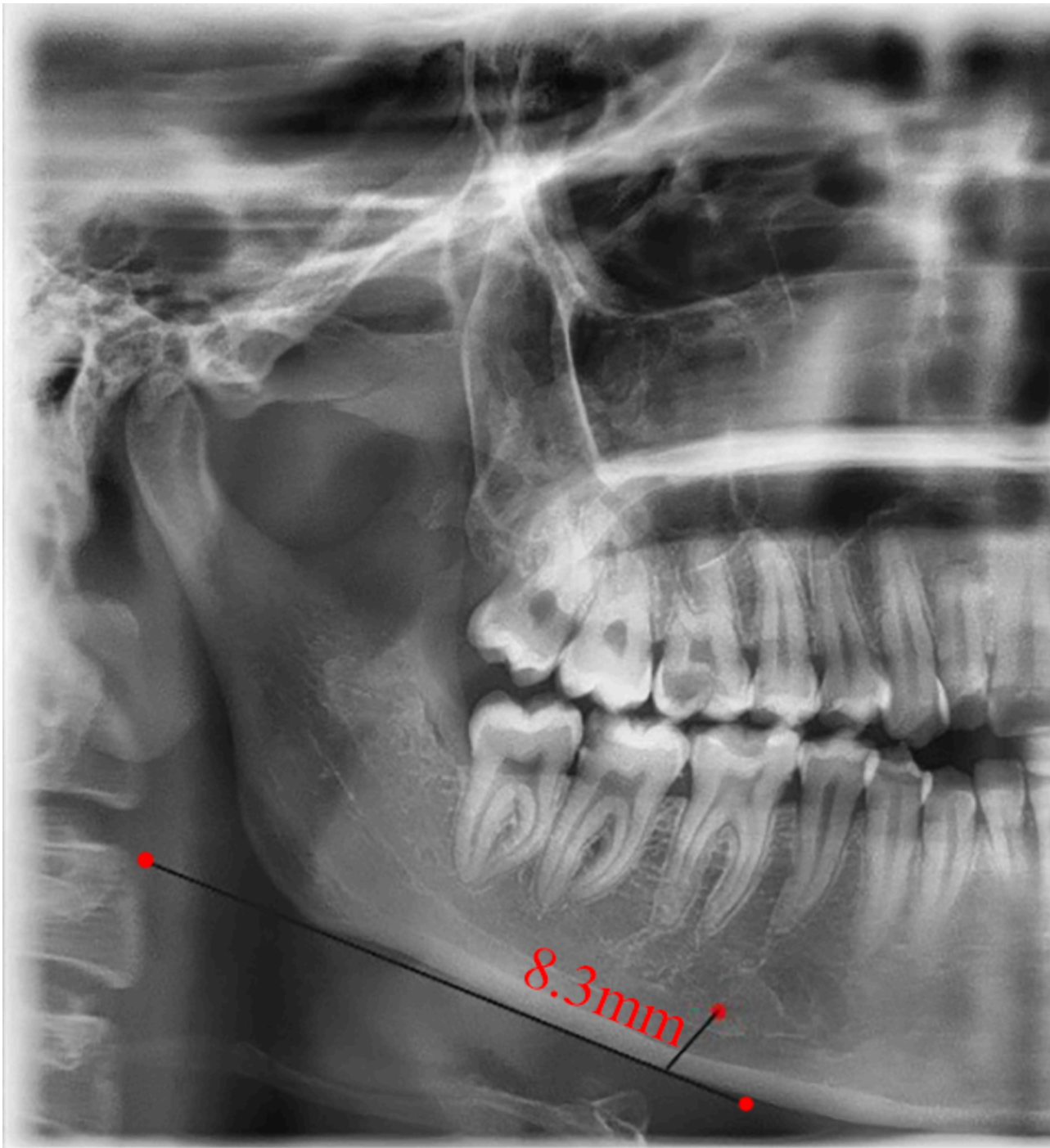


Figure 5

Measurement of the distance between the superior margin of the mental foramen and the inferior border of the mandibular ramus (millimeters) on OPG

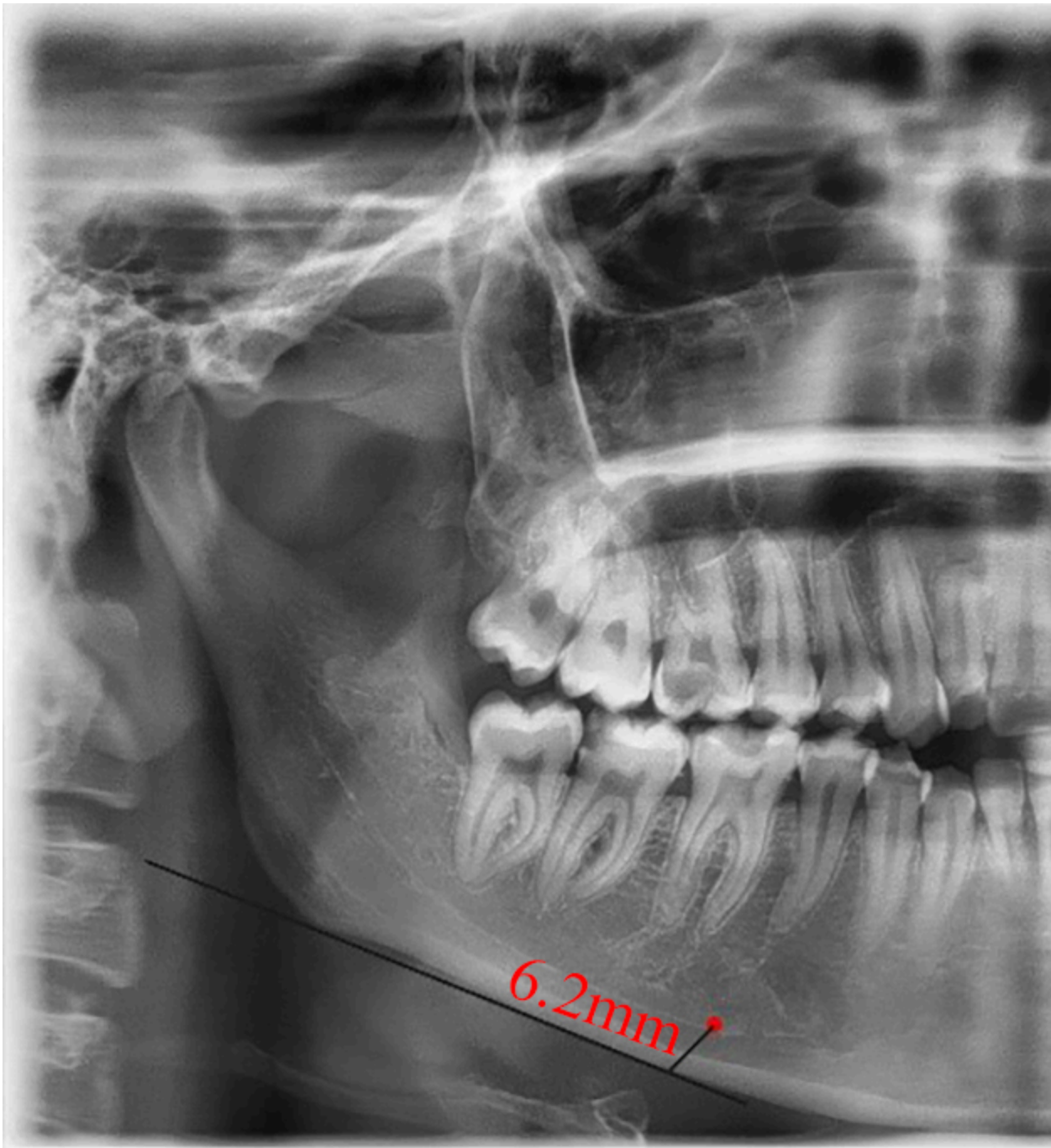


Figure 6

Measurement of the distance between the inferior margin of the mental foramen and the inferior border of the mandibular ramus (millimeters) on OPG

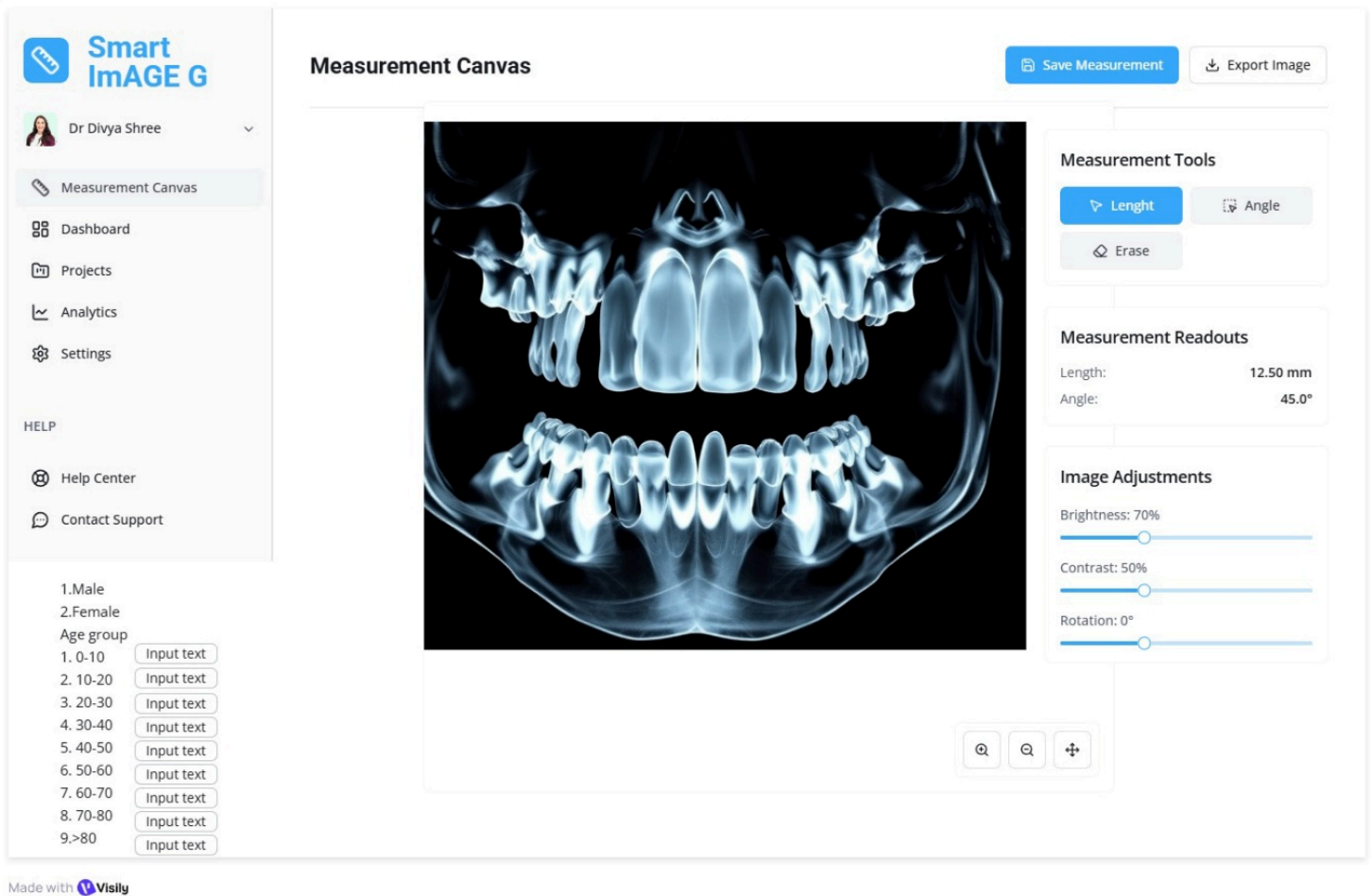


Figure 7

Prototype of the Smart ImAGE G digital measurement tool showing calibrated linear and angular measurements on a panoramic radiograph for dento-maxillofacial osteometric analysis and forensic age estimation

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