



Accuracy of alveolar bone height and thickness measurements in cone beam computed tomography: a systematic review and meta-analysis

Yuan Li, BA,^{a,*} Shiyong Deng, BA,^{a,*} Li Mei, PhD,^{b,*} Jialing Li, MA,^c Meiyao Qi, BA,^a Sihui Su, BA,^a Yu Li, PhD,^d and Wei Zheng, PhD^a

Objective. The aim of this study was to systematically review and assess the accuracy of cone beam computed tomography (CBCT) in the measurement of alveolar bone height and thickness.

Study Design. MEDLINE, Embase, the Cochrane Library, the China National Knowledge Infrastructure, and the gray literature were searched to identify all relevant articles published before July 2018. The Quality Assessment of Measurement Accuracy Studies tool was used to assess the quality of the included studies. Meta-analysis was performed to analyze the mean differences in alveolar bone height and thickness measurements between CBCT and gold standard references (direct measurement on human skulls or live patients).

Results. In total, 28 studies were included in the qualitative synthesis, and 18 were included in the quantitative synthesis. The meta-analysis results showed that the mean differences between CBCT measurements and the gold standard references for alveolar bone height (mean difference = 0.03 mm; 95% confidence interval -0.03 to 0.08; $P = .382$) and alveolar bone thickness (mean difference = 0.11 mm; 95% confidence interval -0.02 to 0.24; $P = .088$) were not statistically significant.

Conclusions. Current evidence suggests that there is no significant difference between CBCT and the gold standard references for the measurement of alveolar bone height and thickness. (Oral Surg Oral Med Oral Pathol Oral Radiol 2019;128:667–679)

Accurate measurement of alveolar bone height and thickness is of significant clinical importance in periodontal, orthodontic, and implant treatments. For example, reductions in alveolar bone height and thickness have been found to be associated with labial flaring, extrusion, rotation, spacing, and drifting of the teeth, often resulting in a complex malocclusion that necessitates an interdisciplinary treatment approach.¹ The height, thickness, volume, and quality of alveolar bone play a crucial role in determining not only the optimal location and prognosis for dental implantation but also the extent of orthodontic tooth movement.²

Since the late 1990s, cone beam computed tomography (CBCT) has become a widely used modality to qualitatively and quantitatively evaluate alveolar bone conditions.³ Advantages of CBCT include 3-dimensional visualization of anatomic structures, greater precision for diagnosis and analysis than with

traditional 2-dimensional radiography,^{4,5} and reduced cost and lower radiation exposure compared with multi-detector computed tomography.⁶ A number of studies have demonstrated that CBCT can be used to measure alveolar bone height and thickness with accuracy and reliability.⁷⁻⁹ However, some studies found significant measurement differences in CBCT and suggested that further attention should be paid to defining the limitations of CBCT measurements.^{10,11} This may have resulted from the variations in those studies, such as the different samples (human dry skulls, fresh skulls, and live patients' heads) and voxel sizes used for the CBCT measurements. The accuracy of CBCT in the measurements of alveolar bone height and thickness still remains controversial.

The aim of this systematic review was to assess the accuracy of alveolar bone height and thickness measurements with CBCT in comparison with the gold standard references (physical direct measurement).

MATERIALS AND METHODS

This systematic review and meta-analysis followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses statement guideline.¹² The review was not registered before data collection.

Statement of Clinical Relevance

Because cone beam computed tomography is widely used in dental clinical diagnosis, it is of great importance to assess its efficacy. The present study summarizes the existing evidence and proposes a choice of imaging tools to clinicians interested in alveolar bone assessment.

^aState Key Laboratory of Oral Diseases, National Clinical Research Center for Oral Diseases, Department of Oral and Maxillofacial Surgery, West China Hospital of Stomatology, Sichuan University, China.

^bDiscipline of Orthodontics, Department of Oral Sciences, Sir John Walsh Research Institute, Faculty of Dentistry, University of Otago, New Zealand.

^cDepartment of Orthodontics, Nanjing Stomatological Hospital, Medical School of Nanjing University, China.

^dState Key Laboratory of Oral Diseases, National Clinical Research Center for Oral Diseases, Department of Orthodontics, West China Hospital of Stomatology, Sichuan University, China.

*These authors contributed equally to this work.

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Search strategy and databases

A systematic search to identify all the relevant studies was conducted in the following 4 databases: MEDLINE (via PubMed; no restrictions were placed on language or year of publication), Embase, the Cochrane Library, and the Chinese National Knowledge Infrastructure. The search strategy (Table I) included controlled vocabulary and free terms. It was developed for MEDLINE and adapted for the other databases. A supplemental manual search was conducted by reviewing the reference lists of the related papers and review articles. The gray literature was searched on Clinical-trial.gov, Open Grey, and the World Health Organization’s International Clinical Trial Registry Platform. All searches were conducted in July 2018.

Selection criteria

The selection criteria used in this systematic review were as follows: (1) human samples (not animal models) without any restriction on age and periodontal condition; (2) measurements of alveolar bone height or thickness; and (3) investigation of the accuracy of measurements, as compared between CBCT scans and the gold standard reference (direct measurement on human skulls or live patients’ heads).

Data extraction

Two reviewers (Y.L. and S.D.) screened the titles and abstracts of the identified studies independently and in duplicate. Consensus was obtained by discussion and consultation with a third reviewer (L.M.) to resolve any disagreements during study selection and data extraction. The reasons for exclusion of studies are noted in Figure 1. The corresponding authors of the included studies were contacted, as needed, to locate unpublished material or to obtain missing data.

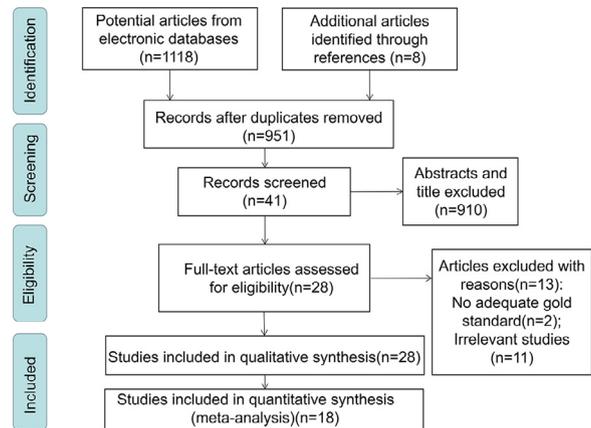


Fig. 1. Systematic review flow diagram.

The following data items were collected: author and year of publication, country, sample properties, sample size, baseline characteristics (age and gender), measurement region, CBCT parameters, number of examiners and measurements, measurement types (alveolar bone height or thickness) and methods, gold standard references, and outcomes.

Methodologic quality appraisal

The risk of bias was assessed by 2 independent dental investigators (Y.L. and S.D). Each study was assessed by using the Quality Assessment of Measurement Accuracy Studies (QUAMAS) tool, as described in the literature.^{13–17} The QUAMAS tool consists of 3 domains: study design, study measurement, and statistical analysis (Table II). The maximum score of a study was 15. Studies that scored not less than 10 were deemed high quality, scores between 7.5 and 9.5 were deemed medium quality, and those scoring less than 7.5 were deemed low quality (see Table II). The Quality Assessment of Diagnostic Accuracy Studies tools

Table I. Search strategies used in the study

MEDLINE	#1	Alveolar bone [Title/Abstract]
	#2	(CBCT [Title/Abstract] OR Spiral Cone Beam Computerized Tomography [Title/Abstract] OR Cone Beam Computed Tomography [Title/Abstract] OR Cone-Beam Computerized Tomography [Title/Abstract] OR Cone-Beam [Title/Abstract] OR Cone Beam [Title/Abstract] OR Cone-Beam CT [Title/Abstract] OR Cone Beam CT [Title/Abstract] OR Helical Cone Beam CT [Title/Abstract] OR “Spiral Cone-Beam Computed Tomography” [Mesh] OR “Cone-Beam Computed Tomography” [Mesh])
	#3	#1 AND #2
Embase	#1	“cone beam computed tomography”/exp OR “cone beam computed tomography” OR “cbct” OR “cone-beam computerized tomography” OR “cone-beam” OR “cone beam” OR “cone-beam ct” OR “cone beam ct”
	#2	“alveolar bone”/exp
	#3	#1 AND #2
Cochrane Library	#1	MeSH descriptor: [Cone-Beam Computed Tomography] explode all trees
	#2	Alveolar bone: Ti, ab, kw (Word variations have been searched)
	#3	#1 and #2
Chinese National Knowledge Infrastructure	#1	Cone-beam Computed Tomography OR Cone-beam CT OR CBCT
	#2	Alveolar bone
	#3	#1 and #2

Table II. The QUAMAS (Quality Assessment of Measurement Accuracy Studies) tool used in the study

Parameter of evaluation			Score
Study design (5√)	A	Objective clearly formulated (√)	1
	B	Randomized sample (√)	1
	C	Sample size: Considered adequate (√)	1
	D	Similar baseline characteristics (√)	1
	E	Selection criteria: Clearly described and adequate (√)	1
Study measurement (5√)	F	Measurement method is appropriate (√)	1
	G	Gold standard is appropriate (√)	1
	H	Adequate examiners and independent measurement (√)	1
	I	Reliability: Described and adequate level of agreement (√)	1
	J	Appropriate examination time interval (√)	1
Statistical analysis (5√)	K	Statistical analysis is appropriate for data (√)	1
	L	Reliability: intra-examiner (√) and inter-examiner (√)	2
	M	Statistical significance level: P value (√) and confidence intervals (√)	2
Total			15

One award (√) indicates that the study fulfilled the concern.

(i.e. QUADAS-1 and -2), designed for the quality assessment on diagnostic accuracy (instead of measurement accuracy) of studies, were not used for this study because of their unsuitability.

Statistical analysis

Meta-analyses of alveolar bone height and thickness were performed to analyze the mean differences between CBCT and the gold standard reference (physical direct measurement). The means and standard deviations of the measurement outcomes were extracted from each study. If the averages and standard deviations of several subgroups, such as the outcomes of different tooth positions without providing overall data, were reported, a formula (Figure 2) was used to combine those data, according to the literature.¹⁸ Authors of the studies that presented inadequate raw data were contacted and requested to supply the analysis data or the raw data.

Cochran’s Q statistics and I² statistics were used to characterize the heterogeneity of the included studies.

$$\bar{x}_T = \frac{\sum_{i=1}^m n_i \bar{x}_i}{\sum_{i=1}^m n_i}$$

$$\begin{aligned} (\sum_{i=1}^m n_i - 1)SD_T^2 &= \sum_{i=1}^m \sum_{j=1}^{n_i} (x_{ij} - \bar{x}_T)^2 = \sum_{i=1}^m \sum_{j=1}^{n_i} (x_{ij} - \bar{x}_i + \bar{x}_i - \bar{x}_T)^2 \\ &= \sum_{i=1}^m \sum_{j=1}^{n_i} (x_{ij} - \bar{x}_i)^2 + \sum_{i=1}^m \sum_{j=1}^{n_i} (\bar{x}_i - \bar{x}_T)^2 \\ &\quad + 2 \sum_{i=1}^m [(\bar{x}_i - \bar{x}_T)(\sum_{j=1}^{n_i} x_{ij} - n_i \bar{x}_i)] \\ &= \sum_{i=1}^m (n_i - 1)SD_i^2 + \sum_{i=1}^m n_i (\bar{x}_i - \bar{x}_T)^2 \end{aligned}$$

$$SD_T = \sqrt{\frac{\sum_{i=1}^m (n_i - 1)SD_i^2 + \sum_{i=1}^m n_i (\bar{x}_i - \bar{x}_T)^2}{(\sum_{i=1}^m n_i - 1)}}$$

Fig. 2. Formula used to combine the results from different subgroups.

When I² was greater than 50%, data were synthesized by using the random effect model; otherwise the fixed effect model was employed. Funnel plots and Egger tests were used to determine if there was any publication bias. Sensitivity analysis and subgroup analysis were conducted to explore the heterogeneity and to assess the robustness of the pooled results. All analyses were performed by using the software STATA 12.0 (StataCorp, College Station, TX), with P < .05 considered statistically significant.

RESULTS

Study selection

A flowchart of the study selection process is shown in Figure 1. In total, 1126 articles were retrieved from the initial search of all sources. After screening the titles and abstracts, 1085 records (175 duplicates and 910 irrelevant) were excluded. As a result, 41 articles remained for full-text assessment; on the basis of the predetermined eligibility criteria, 13 articles were excluded. Finally, 28 studies^{7-9,19-43} were included in the systematic review.

Study characteristics

The 28 studies included in the review were all published between 2008 and 2018, with 2940 teeth from 367 samples (142 patients, 157 dry skulls, and 68 fresh skulls) included in the studies (Table III). The ages of the sample populations ranged from 12 to 97 years, and 52.4% of sample patients were males. Information regarding the sites of the investigations, sample types and sizes, age and gender of patients, measurement regions, CBCT exposure parameters, and examination parameters is provided in Table III.

All 28 studies used direct physical measurement as the gold standard reference (see Table III, Table IV). Twenty-two studies evaluated the measurement accuracy of alveolar bone height,^{7-9,19,20,22-30,32-34,36,38-40,42}

Table III. General information of the included studies

<i>First author (year)</i>	<i>Country</i>	<i>Sample type</i>	<i>Sample size (head/teeth)</i>	<i>Baseline characteristics (age, gender)</i>	<i>Measurement region</i>	<i>CBCT parameters</i>	<i>Number of examiners/ measurement times</i>
Amarnath GS (2015) ⁷	India	Dry edentulous mandibles	15/30	Unknown	Posterior teeth region	120 kVp, 3-8 mA, 0.5 mm nominal focal spot size	Unknown
Alkan BA (2015) ²⁹	Turkey	Dry skulls	10/36	Unknown	Randomly chosen	120 kVp, 5 mA, 9.6 seconds, 0.3 mm voxel size	2/twice
Bohner LOL (2017) ³⁰	Brazil	Dry maxillae	6/18	Unknown	Unknown	70 kVp, 6.3 mA, voxel size 0.18 mm; 75 kVp, 7.0 mA, voxel size 0.125 mm	Unknown/3 times
Castro-Ruiz CT (2015) ³¹	Peru	Patients	12/62	Unknown	Unknown	Unknown	2/twice
Chan HL (2017) ³²	USA	Fresh skulls	6/144	3 males and 3 females (age 66 to ~89 years)	Anterior and posterior teeth region	120 kVp, 18.66 mAs, 20 seconds, resolution 80 μm	1/unknown
Chan HL (2018) ³³	USA	Fresh skulls	7/17	4 males and 3 females (mean age 82 +/- 11.7 years)	Anterior and posterior teeth region	120 kVp, 18.66 mAs, 20 seconds, resolution 80 μm	1/unknown
Cook VC (2015) ⁸	USA	Fresh skulls	12/65	7 males and 5 females (mean age 77 years)	Anterior and posterior teeth region	120 kVp, 5 mA, 26.9/8.9/4.8 seconds, 0.2/0.3/0.3 mm voxel size	1/2 times
Fang D (2012) ³⁴	China	Dry mandibles	8/59	Unknown	Anterior and posterior teeth region	78 kV, 13 mA, 12.14 seconds	2/twice
Feng Y (2012) ¹⁹	China	Fresh skulls	8/200	Unknown	Anterior and posterior teeth region	110 kV, 4.84 to ~19.88 mA, 4.5 seconds	Unknown/3 times
Fu JH (2010) ³⁵	USA	Fresh skulls	22/100	16 males and 6 females (age 33 to ~97 years)	Unknown	120 kVp, 18.66 mAs, 20 seconds	1/unknown
Grimard B (2009) ²⁰	USA	Patients	29/35	17 males and 12 females (age 35 to ~65 years)	Anterior and posterior teeth region	15-inch, 1680*1050-pixel resolution, 18 seconds	1/unknown
Lund H (2010) ²²	Sweden	Dry skulls; patients	1/10; 13/26	Unknown; 7 boys and 6 girls (age 12 to ~18 years)	Anterior and posterior teeth region	60*60 mm volume, 360° rotation, 17.5 seconds, 75 kV, and 4.0–5.5 mA	1/twice; 5 times
Li K (2016) ³⁷	China	Patients	30/34	13 males and 17 females (age 12 to ~18 years)	Unknown	6# volume, 36 seconds, 0.625 mm construction layer thickness	Unknown
Leung CC (2010) ³⁶	USA	Dry skulls	13/334	Unknown	Anterior and posterior teeth region	110 kVp, 2 mA, 9.6 seconds, voxel size 0.38 mm	1/once
Loubele M (2008) ²¹	Belgium	Fresh skulls	1/11	Unknown	Anterior and posterior teeth region	120/70 kVp, 90/74 mA, 0.75/17.5 seconds	2/unknown
Menezes CC (2016) ⁹	Brazil	Dry mandibles	12/72	Unknown	Anterior and posterior teeth region	120 kVp, 36.12/18.45 mAs, 40/20 seconds, 0.2/0.3/0.4 mm voxel size	2/twice
Neves, F.S. (2012) ³⁸	Brazil	Dry edentulous mandibles	8/80	Unknown	Anterior and posterior teeth region	Half scan (180°), 20.27 mA, 7 seconds; full scan (360°), 37.07 mA, 26.9 seconds (0.20 mm voxel size and 120 kVp)	2/once
Pena de Andrade JG (2016) ²⁶	Brazil	Edentulous jaws	6/48	Unknown	Anterior and posterior teeth region	Unknown	Unknown
Patcas R (2012) ²⁴	Switzerland	Fresh skulls	8/48	3 males and 5 females (age 65 to ~95 years)	Anterior teeth region	120 kV, 37.07 mAs, 0.4 mm voxel size	1/twice

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Table III. Continued

First author (year)	Country	Sample type	Sample size (head/teeth)	Baseline characteristics (age, gender)	Measurement region	CBCT parameters	Number of examiners/ measurement times
Patcas R (2012) ²⁵	Switzerland	Fresh skulls	8/48; 61	3 males and 5 females (age 65 to ~95 years)	Anterior teeth region	120 kV, 5 mA, 0.125/0.4 mm voxel size	1/twice
Patcas R (2015) ²³	Switzerland	Fresh skulls	8/48	3 males and 5 females (age 65 to ~95 years)	Anterior teeth region	120 kV, 37.03 mA, 0.125 mm voxel size	Unknown
Sheikhi M (2012) ²⁷	Iran	Dry skulls	6/30	Unknown	Anterior and posterior teeth region	85 kVp, 7 mA, 14 seconds, 0.15 mm voxel size	2/3 times
Timock AM (2011) ³⁹	USA	Fresh skulls	12/65	7 males and 5 females (age 55 to ~89 years)	Anterior and posterior teeth region	120 kVp, 3–8 mA, 8.9 seconds, 0.3 mm voxel size	2/3 times
Vasconcelos TV (2015) ⁴⁰	Brazil	Dry, fully edentulous mandibles	8/80	Unknown	Anterior and posterior teeth region	0.20 mm of voxel size, full-scan mode, 120 kVp, 37.07 mA, 26.9 seconds	1/once
Wang W (2015) ⁴¹	China	Patients	25/25	15 males and 10 females (age 18 to ~44 years)	Unknown	Unknown	Unknown
Wang X (2017) ⁴²	China	Patients	56/1120	21 males and 35 females (age 19 to ~60 years)	Anterior and posterior teeth region	90 kV, 13 mA, 12 seconds	1/twice
Zhong J (2012) ²⁸	China	Dry mandibles; patients	10/60; 10/22	Unknown	Anterior teeth region	65~70 kV, 3.5~4.0 mA	1/twice
Zhao L (2016) ⁴³	China	Patients	20/23	14 males and 6 females (age 26 to ~66 years)	Molars region	110 kVp, 12 to ~17 mA	1/twice

and 13 studies evaluated the measurement accuracy of alveolar bone thickness.^{7,8,21,26,28,30,31,33, 35,37,39,41,43}

The types of samples consisted of dry skulls,^{7,9,22,26–30,34,36,38,40} fresh skulls,^{8,19,21,23–25,32,33,35,39} and live patients' heads.^{20,28,31,37,41,42}

Alveolar bone height was measured from the alveolar crest to the cusp tip,^{13,24,28–30,41,44} cemento-enamel junction,^{9,19,20,22,29,32,34,42} or others (i.e., the inferior point on the mandible,^{7,27,38} the superior cortical border of the mandibular canal,⁴⁰ the implant platform,^{30,33} or the alveolar fossa²⁸).

Alveolar bone thickness was measured at places either 4 mm or less (i.e., 1 mm, 2 mm, 3 mm, or 4 mm)^{7,8,28,33, 35,39,41} or greater than 4 mm (i.e., 5 mm, 8 mm, and 10 mm)^{7,30,31} from the crest of the alveolar ridge. There was a large variation in the CBCT voxel size (from 0.125 mm to 0.4 mm) among the studies included.

Quality of studies

Among the 28 included articles, 17 studies^{8,9,19,22–25,27–29,31,34–36,38–40} were rated as high quality, 7 studies^{20,21,30,32,33,37,42} were of medium quality, and 4 studies^{7,26,41,43} were of low quality (Table V). The major methodologic limitations were inadequate numbers of examiners, failure to design or mention independent measurements, no randomization, and the lack of statistical analysis of reliability.

Synthesis of results

A meta-analysis was performed on the 18 studies with homogeneity.^{7–9,29–41,43} The other 10 studies were excluded from the meta-analysis because they only reported the mean differences between CBCT and gold standard references without providing the raw data for each measurement. Corresponding authors were contacted by email to request their original experimental data, but no response was received at the time this review was submitted. In the study by Amarnath et al.,⁷ 3 different measurement methods and results were reported, and these data were included in the meta-analysis separately.

Meta-analysis of alveolar bone height (Figure 3), which was based on 13 studies (2260 teeth) with no statistical heterogeneity ($P = .131$; $I^2 = 31.5\%$), revealed that the mean difference between CBCT and the gold standard reference was not statistically significant (mean difference = 0.03 mm; 95% confidence interval [CI] –0.03 to 0.08; $P = .382$). The funnel plots (Figure 4) and Egger tests demonstrated no publication bias (Egger test: $P = .148$).

Meta-analysis of alveolar bone thickness (Figure 5), which was based on 10 studies (481 teeth) with no statistical heterogeneity ($P = 0.58$; $I^2 = 0\%$), showed that the mean difference between CBCT and gold standard

Table IV. Measurement information of the included studies

<i>First author (year)</i>	<i>Alveolar bone measurement</i>	<i>Measurement methods</i>	<i>Gold standard reference</i>	<i>Outcomes</i>
Amarnath GS (2015) ⁷	Height; thickness	<i>Height:</i> AC—most inferior and superior points on the mandible <i>Thickness:</i> 2/5/8 mm—from the crest of the alveolar ridge.	Direct measurement	There was no significant difference between the 2 measurements.
Alkan BA (2015) ²⁹	Height	CEJ–AC	Direct measurement	<i>Buccal:</i> 2.50 ± 1.26(DM)/2.61 ± 1.15(CBCT); <i>P</i> < .001 <i>Lingual:</i> 3.14 ± 0.77(DM)/2.94 ± 0.81(CBCT); <i>P</i> < .001
Bohner LOL (2017) ³⁰	Height; thickness	<i>Height:</i> AC–IP <i>Thickness:</i> 5 mm—above the apical point of the implant	Direct measurement	<i>Height:</i> 1.78 ± 1.33 (DM)/1.80 ± 1.09 (CBCT) <i>Thickness:</i> 1.50 ± 0.84 (DM)/1.61 ± 1.27 (CBCT)
Castro-Ruiz CT (2015) ³¹	Thickness	10 mm—from the crest of the alveolar ridge	Direct measurement	3.39 ± 1.56 (DM)/3.42 ± 1.41 (CBCT); <i>P</i> = .207 No statistical difference was found.
Chan HL (2017) ³²	Height	CEJ–AC	Direct measurement	2.71 ± 1.04 (DM)/2.51 ± 0.82 (CBCT); <i>P</i> = .018
Chan HL (2018) ³³	Height; thickness	<i>Height:</i> AC–IP <i>Thickness:</i> 1 mm—from the crest of the alveolar ridge	Direct measurement	<i>Height:</i> 2.62 ± 1.78 (DM)/2.82 ± 2.24 (CBCT); <i>P</i> = .24 <i>Thickness:</i> 0.96 ± 0.85 (DM)/ 1.19 ± 0.75 (CBCT); <i>P</i> < .05
Cook VC (2015) ⁸	Height; thickness	<i>Height:</i> CT–AC <i>Thickness:</i> 3 mm—from the crest of the alveolar ridge	Direct measurements	<i>Height:</i> 12.32 ± 2.22 (DM)/12.34 ± 2.20 (long scan CBCT)/12.34 ± 2.21 (default scan CBCT)/12.34 ± 2.05 (short scan CBCT) <i>Thickness:</i> 0.52 ± 0.33(DM)/0.52 ± 0.33(long scan CBCT)/0.54 ± 0.35(default scan CBCT)/0.57 ± 0.33 (short scan CBCT) No statistical differences were found with any of BBH or BBT measurements.
Fang D (2012) ³⁴	Height	CEJ–AC	Direct measurement	<i>Anterior:</i> 3.91 ± 0.69 (DM)/3.96 ± 0.65 (CBCT) <i>Premolar:</i> 2.85 ± 0.31 (DM)/2.83 ± 0.32 (CBCT) <i>Molar:</i> 3.31 ± 0.47 (DM)/3.28 ± 0.47 (CBCT) No significant difference were found between the measurement by the CBCT images and by Vernier calipers (<i>P</i> > .05)
Feng Y (2012) ¹⁹	Height	CEJ–AC; CT–AC	Direct measurement	The values of CBCT measurement were smaller than those of the direct measurement. Significant difference was found in the values of CT–AC and CEJ–AC The mean deviations were –0.238 mm and –0.208 mm.
Fu JH (2010) ³⁵	Thickness	2 mm—from the crest of the alveolar ridge	Direct measurement	<i>Buccal:</i> 0.83 ± 0.32 (DM)/0.94 ± 0.35 (CBCT); <i>P</i> = .057 <i>Lingual:</i> 1.09 ± 0.35 (DM)/1.21 ± 0.39 (CBCT); <i>P</i> = .105 No statistically significant differences were observed between the clinical and CBCT measurements.
Grimard B (2009) ²⁰	Height	CEJ–AC	Direct measurement	CBVT correlated strongly with surgical measurements (<i>r</i> = 0.89–0.95) No significant difference was seen between CBCT and surgical measurements.
Lund H (2010) ²²	Height	CEJ–AC	Direct measurement	The in vitro mean difference between physical and radiographic measurements was –0.04 mm (SD 0.54) for marginal bone level. In vivo, the error was less than 0.40 mm for marginal bone level assessments and statistically insignificant.
Li K (2016) ³⁷	Thickness	Unknown	Direct measurement	5.01 ± 0.89 (DM)/4.96 ± 0.91 (CBCT); <i>P</i> = .830 The thickness measured by CBCT showed no statistical difference compared with actual measurement results.

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Table IV. Continued

<i>First author (year)</i>	<i>Alveolar bone measurement</i>	<i>Measurement methods</i>	<i>Gold standard reference</i>	<i>Outcomes</i>
Leung CC (2010) ³⁶	Height	CT–AC	Direct measurement	10.3 ± 2.1(DM)/10.6 ± 1.9(CBCT)
Loubele M (2008) ²¹	Thickness	Distance between holes derived from corresponding markers at buccal and lingual sides	Direct measurement	The accuracy of the linear measurements was 0.35 ± 1.31 mm (U70u)* and 0.06 ± 1.23 mm (U90u)* for the Somatom Volume Zoom, 0.24 ± 1.20 mm (H60s)* and 0.54 ± 1.14 mm (H30s)* for the Sensation 16, and 0.09 ± 1.64 mm for the Accuitomo 3-D. No significant difference was found.
Menezes CC (2016) ⁹	Height	CEJ–AC	Direct measurement	A high accuracy for measurements of bone crest level was observed for all CBCT definitions, except for the mandibular incisors with use of the 0.4-mm voxel size.
Neves FS (2012) ³⁸	Height	AC—most inferior and superior points on the mandible	Direct measurement	Except the bone height of the second molar region in full scan mode ($P = .02$), Wilcoxon’s signed rank test did not show statistical significant difference with the gold standard ($P > .05$).
Pena de Andrade JG (2016) ²⁶	Height; thickness	Unknown	Direct measurement	No statistically significant difference between the measurements obtained from CBCT images and those obtained from actual measurements for all the evaluated sites (molars, premolars, and anterior teeth)
Patcas R (2012) ²⁴	Height	CT–AC	Direct measurement	Radiologic measurements were accurate, with a mean difference from anatomic measurements of 0.14 mm (CBCT). These differences were not statistically significant.
Patcas R (2012) ²⁵	Height	CT–AC	Direct measurement	Bony measures obtained with CBCT were accurate and differed only slightly from the physical findings. The mean differences, ranging from 0.13 to 10.13 mm, were statistically not significant.
Patcas R (2015) ²³	Height	CT–AC	Direct measurement	The mean difference for all visualization protocols was very close to 0 with the exception of isosurface (0.37 mm).
Sheikhi M (2012) ²⁷	Height	AC—most inferior and superior points on the mandible	Direct measurement	The mean difference between physical measurements and radiographic measurements was 0.05 ± 0.45. There was a statistically significant difference ($P < .05$), but not clinically significant.
Timock AM (2011) ³⁹	Height; thickness	<i>Height:</i> CT–AC <i>Thickness:</i> 3 mm—from the crest of the alveolar ridge	Direct measurement	<i>Height:</i> 12.32 ± 2.22 (DM)/12.34 ± 2.21 (CBCT) <i>Thickness:</i> 0.52 ± 0.33 (DM)/0.54 ± 0.35 (CBCT) CBCT measurements did not differ significantly from direct measurements.
Vasconcelos TV (2015) ⁴⁰	Height	AC—superior cortical border of the mandibular canal	Direct measurement	19.12 ± 0.62 (DM)/19.01 ± 0.61 (CBCT, OnDemand3-D)/19.37 ± 0.62 (CBCT, XoranCat)/18.97 ± 0.61 (CBCT, KDIS3-D) There was no statistical significant difference between the measurements obtained with the different software packages and the gold standard ($P > .05$).
Wang W (2015) ⁴¹	Thickness	4 mm—from the crest of the alveolar ridge	Direct measurement	1.4 ± 0.2 (DM)/1.4 ± 0.32 (CBCT); $P > .05$
Wang X (2017) ⁴²	Height	CEJ–AC	Direct measurement	There was no significant difference between CBCT and clinical probing ($P > .05$).
Zhong J (2012) ²⁸	Height; thickness	<i>Height:</i> AC—alveoli fossa <i>Thickness:</i> 1 mm—from the crest of the alveolar ridge	Direct measurement	In vitro, no significant difference was found between CBCT and direct measurements. In vivo, no significant difference was found between CBCT and direct measurements, except for the labial alveolar height.
Zhao L (2016) ⁴³	Thickness	Unknown	Direct measurements	10.69 ± 1.60 (DM)/11.42 ± 1.65 (CBCT); $P = .002$

AC, alveolar crest; CBCT, cone beam computed tomography; CEJ, cemento enamel junction; CT, cusp tip; DM, direct measure; IP, implant platform.

*U70u and U90u are 2 high-resolution kernels to reconstruct images. The images were also reconstructed with 2 different filters: H30s, a soft-tissue kernel, and H60s, a bone kernel.

Table V. Quality assessment of the included studies using the QUAMAS (Quality Assessment of Measurement Accuracy Studies) tool

Studies	Study design					Study measurement					Statistical Analysis			Total
	A	B	C	D	E	F	G	H	I	J	K	L	M	
Amarnath GS (2015) ⁷	1	0.5	0	0.5	0	1	1	0.5	0	0	1	0	1	6.5
Alkan BA (2015) ²⁹	1	1	0	0.5	0	1	1	0.5	1	1	1	2	1	11
Bohner LOL (2017) ³⁰	1	0.5	0	0.5	0	1	0.5	0.5	0	1	1	0	2	8
Castro-Ruiz CT (2015) ³¹	1	0.5	1	0.5	1	1	1	0.5	1	1	1	2	1	11.5
Chan HL (2017) ³²	1	0.5	1	1	0	1	0	0	1	0.5	1	0	2	9
Chan HL (2018) ³³	1	0.5	0	1	0	1	0	0	1	0.5	1	0	2	8
Cook VC (2015) ⁸	1	0.5	1	0.5	1	1	1	0	1	1	1	1	2	12
Fang D (2012) ³⁴	1	0.5	1	0.5	1	1	1	1	1	1	1	2	1	12
Feng Y (2012) ¹⁹	1	0.5	1	0.5	1	1	1	0.5	1	1	1	1	2	12
Fu JH (2010) ³⁵	1	0.5	1	0	0.5	1	1	0	1	0.5	1	2	1	10.5
Grimard B (2009) ²⁰	1	1	0	0	1	1	0	0	0	0.5	1	2	2	9.5
Lund H (2010) ²²	1	1	0	1	0	1	1	0	1	1	1	1	1	10
Li K (2016) ³⁷	1	0.5	0	1	1	0.5	0.5	0.5	0	0.5	1	0	1	7.5
Leung CC (2010) ³⁶	1	0.5	1	0.5	1	1	1	0	1	0	1	1	1	10
Loubele M (2008) ²¹	1	0	0	0.5	0	1	1	0.5	1	0.5	1	1	1	8.5
Menezes CC (2016) ⁹	1	0.5	1	0.5	0	1	1	0	1	1	1	2	1	11
Neves FS (2012) ³⁸	1	1	1	0.5	1	1	1	0.5	1	0.5	1	2	1	12.5
Pena de Andrade JG (2016) ²⁶	1	0.5	0	0.5	0	0	1	0.5	0	0.5	1	0	1	6
Patcas R (2012) ²⁴	1	0.5	0	1	0	1	1	0	1	1	1	1	2	10.5
Patcas R (2012) ²⁵	1	0.5	1	1	0	1	1	0	1	1	1	1	2	11.5
Patcas R (2015) ²³	1	0.5	0	1	0	1	1	0.5	1	0.5	1	2	2	11.5
Sheikhi M (2012) ²⁷	1	0.5	0	0.5	0	1	1	0.5	1	1	1	2	1	10.5
Timock AM (2011) ³⁹	1	0.5	1	1	1	1	1	1	1	1	1	2	1	13.5
Vasconcelos TV (2015) ⁴⁰	1	0.5	1	0.5	0	1	1	0	1	0.5	1	1	2	10.5
Wang W (2015) ⁴¹	1	0.5	0	1	1	0.5	1	0.5	0	0.5	0	0	1	7
Wang X (2017) ⁴²	1	0.5	1	0	1	0	0	0	1	1	1	0	1	7.5
Zhong J (2012) ²⁸	1	0.5	1	0.5	1	1	1	0	1	1	1	1	1	11
Zhao L (2016) ⁴³	1	0.5	0	0	1	0	0	0	0	1	1	1	1	6.5

1 = Yes; 0 = No; 0.5 = Unclear.

reference was not statistically significant (mean difference = 0.11 mm; 95% CI -0.02 to 0.24; $P = .088$). The funnel plots (Figure 6) and Egger tests demonstrated no publication bias (Egger test: $P = .533$).

It is worth noting that funnel plots with pseudo-95% CIs and Egger tests were used to assess if there was any publication bias. The pseudo-95% CIs in the funnel plots, which represent the 2 sides of the “funnel,” are an aggregation of 95% CIs for all studies with different sample sizes, rather than the 95% CIs of the result of a single study. Publication bias is assessed by visual observation of the distribution of each study in this confidence interval.

Sensitivity analysis

Sensitivity analyses (Table VI) were performed by excluding the studies with a high risk of bias and by changing the effect models (i.e., fixed and random effect models). No significant changes were identified in the sensitivity analyses, indicating that the meta-analyses had low sensitivity and good stability.

Subgroup analysis

Subgroup analyses (see Table VI) were performed on sample type, measurement method, and CBCT voxel

size to take into account any potential clinical heterogeneity. No significant differences were found in the subgroup analyses (all $P > .05$; see Table VI) indicating that there was no significant difference between CBCT and gold standard references for the measurement of alveolar bone height and thickness.

DISCUSSION

Clinical assessment of the alveolar bone condition mainly includes alveolar bone height, thickness, and defects. A recent systematic review and meta-analysis investigated the precision of CBCT in assessing periodontal bone defects and showed that there was no significant difference between CBCT and in situ measurements of alveolar bone loss.⁴⁴ The accuracy of CBCT in alveolar bone height and thickness measurements is also crucial for precise treatment planning and management of such treatments as dental implants, periodontal surgery, and orthodontic tooth movement. The current review systematically assessed the accuracy of CBCT in alveolar bone height and thickness measurements and found that the mean difference between CBCT and the gold standard reference (physical direct

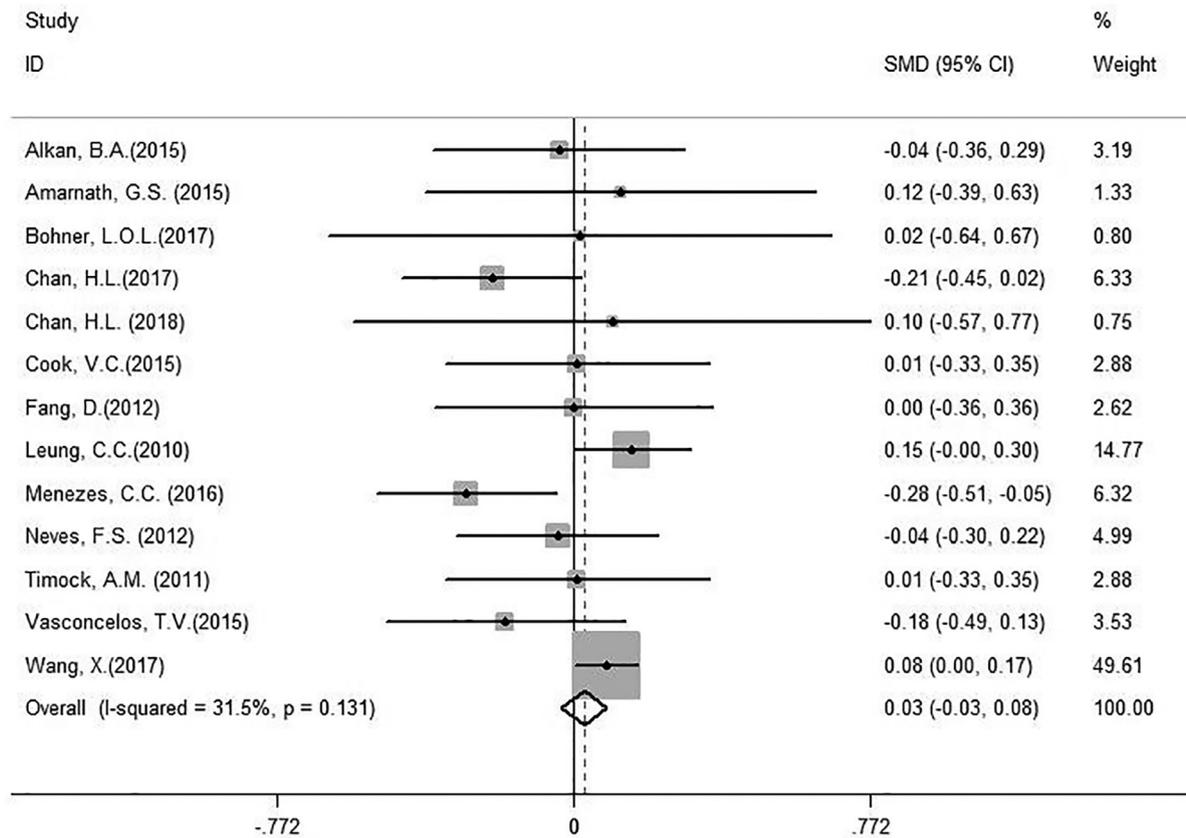


Fig. 3. Meta-analysis of the mean differences between cone beam computed tomography (CBCT) and the gold standard references for alveolar bone height. *CI*, confidence interval; *SMD*, standardized mean difference; *% weight*, weight of data from each article in the meta-analysis.

measurement on skulls or patients) was not significant for either alveolar bone height or thickness, indicating that the accuracy of CBCT is relatively good in alveolar bone height and thickness measurements.

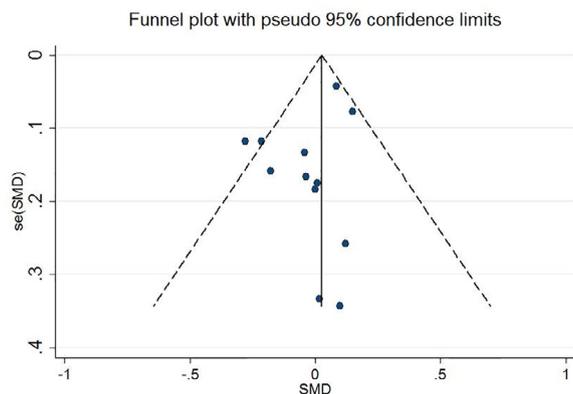


Fig. 4. Funnel plots of potential publication bias for the studies on alveolar bone height. Pseudo-95% confidence intervals: an aggregation of 95% confidence intervals for all studies with different sample sizes.

Among the 28 studies included in this review, 20 studies^{9,20,21,24-26,28,31,35-42} reported no significant differences between CBCT and the gold standard reference for measuring alveolar bone height and/or thickness. The other 8 studies^{19,22,27,29,32,33,36,43} found that the mean differences (ranging from -0.04 mm to 0.23 mm) between CBCT and gold standard references were statistically significant but not clinically significant. After pooling of data, the meta-analysis in the study suggested that there was no significant difference between CBCT and the gold standard reference for the measurements of alveolar bone height and thickness. Sensitivity and subgroup analyses also confirmed the robustness and stability of the meta-analysis results.

There was a large variation in the methods used for measuring alveolar bone height, which was determined as the distance between the alveolar crest to a variety of landmarks, including the cemento-enamel junction,^{9,19,20,22,29,32,34,42} the cusp tip,^{8,19,23-25,36,39} the inferior point of the mandible,^{7,27,38} the superior cortical border of the mandibular canal,⁴⁰ the implant platform,^{30,33} or the alveolar fossa.²⁸ An accurate

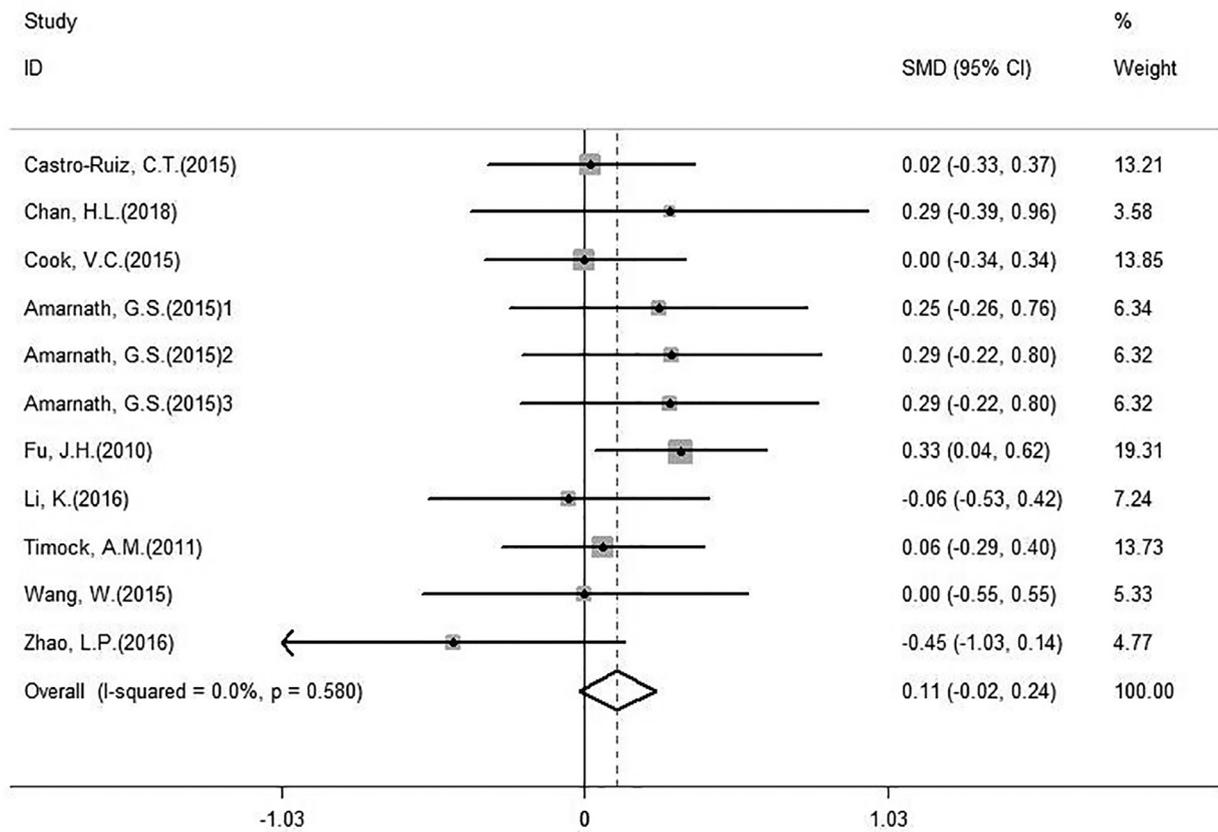


Fig. 5. Meta-analysis of the mean differences of cone beam computed tomography (CBCT) and the gold standard references for alveolar bone thickness. CI, confidence interval; SMD, standardized mean difference; % weight, weight of data from each article in the meta-analysis.

registration of the cementoenamel junction in CBCT images was usually difficult,^{19,29,32} potentially contributing to the deviations in alveolar bone height measurement. However, subgroup analyses on the measurement methods in this review demonstrated that

the measurement difference was even smaller in the methods that used the cementoenamel junction (mean difference = 0.01 mm) than that in the methods that used the cusp tip (0.11 mm) or other landmarks (-0.05 mm).

Although subgroup analyses on the alveolar bone thickness measurement methods did not reveal significant differences, these methods also exhibited wide variations, including the locations of measurement at 1 mm, 2 mm, 3 mm, 4 mm, 5 mm, 8 mm, and 10 mm from the crest of the alveolar ridge. Thus, when making clinical interpretations and applying research findings on alveolar bone thickness measurement with the use of CBCT, it is important to specify the actual location where the thickness was measured.

Approximately one-quarter of the included studies reported direct measurements on live patients' heads. The other studies used fresh human skulls or skulls without soft tissues. Differences in sample type may contribute to the differences in the measurements on skulls and on live patients because the soft tissues on live patients would affect the attenuation coefficient and X-ray beam transmission through the skull.⁴⁵ The

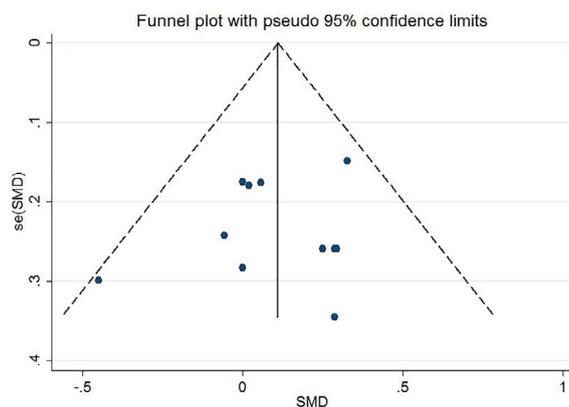


Fig. 6. Funnel plots of potential publication bias for the studies on alveolar bone thickness. Pseudo-95% confidence intervals: an aggregation of 95% confidence intervals for all studies with different sample sizes.

Table VI. Sensitivity analyses and subgroup analyses

Measurements	Results		
	Mean difference	95% Confidence interval	P value
Alveolar bone height			
Original estimate	0.03	[-0.03, 0.08]	.382
Random effect model	-0.02	[-0.10, 0.07]	.733
Exclusion of studies with high risk of bias	-0.04	[-0.12, 0.05]	.405
Subgroup analysis on sample type			
Dry skulls	-0.01	[-0.10, 0.09]	.847
Fresh skulls	-0.10	[-0.26, 0.07]	.251
Live patients' heads	0.02	[-0.08, 0.11]	.554
Subgroup analysis on measurement method			
From alveolar crest to cementoenamel junction	0.01	[-0.06, 0.08]	.701
From alveolar crest to cusp top	0.11	[-0.02, 0.24]	.093
Others	-0.05	[-0.23, 0.12]	.549
Subgroup analysis on voxel size			
≤2 mm	0.02	[-0.04, 0.07]	.961
2 mm	-0.07	[-0.24, 0.10]	.413
3 mm	-0.15	[-0.32, 0.02]	.076
≥3 mm	0.15	[-0.00, 0.30]	.053
Alveolar bone thickness			
Original estimate	0.11	[-0.02, 0.24]	.088
Random effect model	0.11	[-0.02, 0.24]	.088
Exclusion of high risk of bias	0.11	[-0.04, 0.27]	.145
Subgroup analysis on sample type			
Dry skulls	0.28	[-0.02, 0.57]	.065
Fresh skulls	0.16	[-0.02, 0.34]	.079
Live patients' heads	-0.07	[-0.31, 0.16]	.527
Subgroup analysis on measurement method			
≤4 mm	0.16	[-0.01, 0.32]	.059
>4 mm	0.15	[-0.10, 0.40]	.235
Subgroup analysis on voxel size			
0.2 mm	0	[-0.00, 0.00]	1.000
0.3 mm	0.06	[-0.28, 0.40]	.739

routine calibration of the CBCT scanner with a designated phantom to simulate a live patient seems unsuitable for a dry skull. To take into account any potential clinical heterogeneity, subgroup analyses on sample types were performed in the study; no significant differences were found in those analyses, and this helped confirm that the accuracy of CBCT measurements of alveolar bone height and thickness is relatively good.

Different CBCT exposure parameters, such as field of view and voxel size, could influence the quality of the image and contribute to measurement errors.³⁰ Voxel size has been found to have a great impact on the quality of CBCT images. For example, a small voxel size could strengthen the ability of CBCT to distinguish tiny structures, but an increased exposure time and radiation dose to the patient would be required.⁴⁶ It has been suggested that CBCT could be used to measure many structures in the maxillofacial region accurately, but not alveolar bone, with a voxel size of 0.4 mm.⁴⁷ The buccal alveolar bone was found to be too thin to be measured reliably even in the 0.125-mm voxel size protocol.²⁵ Subgroup analyses on the voxel size in the present investigation demonstrated that the larger the voxel size used, the larger was the

measurement error. Therefore, a small voxel size within an appropriate radiation exposure range would result in a relatively accurate measurement. However, some evidence has suggested that voxel size did not affect periimplant fenestration and dehiscence detection.⁴⁸

The QUADAS-1 and -2 tools are usually used as the quality assessment tool for studies on diagnostic accuracy. The current review assessed studies on the measurement accuracy of alveolar bone height and thickness between CBCT and the physical direct measurement rather than the diagnostic accuracy of alveolar bone disease. Therefore, QUADAS was not suitable for this systematic review. In this investigation, the QUAMAS tool, customized according to the literature,¹³⁻¹⁷ was used to assess the quality of the studies.

There are some limitations to our study. Among the 28 studies included in this review, 10 articles were excluded from the meta-analysis because of inadequate presentation of raw data and statistical results. Some studies only recorded the mean difference and standard deviation between CBCT measurements and the gold standard reference without reporting the exact value of each measurement. Although we contacted the

corresponding authors via e-mail and requested their raw data for inclusion in the meta-analysis, we received no responses at the time of writing of this review. This may decrease the statistical power of the meta-analysis. In addition, it has been found that other factors, such as patient head position (rotation and flexion), scan distance, and distortion during CBCT scanning, could also influence the accuracy of measurement.²⁷

Although the radiation burden to patients is relatively low in CBCT in comparison with multidetector CT, the CBCT dose is still higher than that in conventional 2-D imaging, such as periapical and panoramic radiography.³ During the CBCT examination, a slight shift in the position of the patient may result in a decrease in the overall sharpness of the image.⁴⁹ The cost of CBCT is also usually higher than that of 2-D radiography. Data relating to radiation and cost, however, could not be extracted from the articles included in this study. In the literature, CBCT has been recommended only for special cases in which dentists are unable to make definitive diagnoses with conventional radiography.⁵⁰ Therefore, in patients who have significant periodontal diseases, require precise dental implant planning, or need particular orthodontic tooth movement, CBCT could be a good choice when clinical probing and 2-D radiography are inadequate for accurate diagnosis and appropriate therapy.

CONCLUSIONS

Current evidence suggests that there is no significant difference between CBCT and gold standard references (direct measurement on human skulls or live patients) for the measurement of alveolar bone height and thickness.

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- Reprint requests:*
- Wei Zheng
 State Key Laboratory of Oral Diseases & National Clinical Research Center for Oral Diseases
 West China Hospital of Stomatology
 Sichuan University
 14th Renmin South Road Third Section
 Chengdu 610041
 China.
 Zhengwei81101@163.com