Accepted: 17 February 2018

DOI: 10.1111/clr.13142

REVIEW ARTICLE

WILEY CLINICAL ORAL IMPLANTS RESEARCH

Accuracy of linear measurements on CBCT images related to presurgical implant treatment planning: A systematic review

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Abstract

Objective: The aim of this systematic review was to identify, review, analyze, and summarize available evidence on the accuracy of linear measurements when using maxillofacial cone beam computed tomography (CBCT) specifically in the field of implant dentistry.

Material and methods: The search was undertaken in April 2017 in the National Library of Medicine database (Medline) through its online site (PubMed), followed by searches in the Cochrane, EMBASE, ScienceDirect, and ProQuest Dissertation and Thesis databases. The main inclusion criterion for studies was that linear CBCT measurements were performed for quantitative assessment (e.g., height, width) of the alveolar bone at edentulous sites or measuring distances from anatomical structures related to implant dentistry. The studies should compare these values to clinical data (humans) or ex vivo and/or experimental (animal) findings from a "gold standard."

Results: The initial search yielded 2,516 titles. In total, 22 studies were included in the final analysis. Of those, two were clinical and 20 ex vivo investigations. The major findings of the review indicate that CBCT provides cross-sectional images that demonstrate high accuracy and reliability for bony linear measurements on cross-sectional images related to implant treatment. A wide range of error has been reported when performing linear measurements on CBCT images, with both over- and underestimation of dimensions in comparison with a gold standard. A voxel size of 0.3 to 0.4 mm is adequate to provide CBCT images of acceptable diagnostic quality for implant treatment planning.

Conclusions: CBCT can be considered as an appropriate diagnostic tool for 3D preoperative planning. Nevertheless, a 2 mm safety margin to adjacent anatomic structures should be considered when using CBCT. In clinical practice, the measurement accuracy and reliability of linear measurements on CBCT images are most likely reduced through factors such as patient motion, metallic artefacts, device-specific exposure parameters, the software used, and manual vs. automated procedures.

KEYWORDS

CT imaging, diagnosis/clinical assessment, radiology/imaging

1 | INTRODUCTION

The introduction of cone beam computed tomography (CBCT) in dento-maxillofacial radiology (DMFR) almost two decades ago (Ganguly, Ramesh & Pagni, 2016) has resulted in a paradigm shift from planar, two-dimensional (2D) to volumetric, three-dimensional (3D) radiographic visualization (Visconti, Verner, Assis & Devito, 2013). CBCT imaging is currently considered a well-established adjunctive diagnostic, virtual simulation, and treatment planning tool with various clinical applications in disciplines such as implant dentistry (Bornstein, Al-Nawas, Kuchler & Tahmaseb, 2014; Bornstein, Horner & Jacobs, 2017; Guerrero et al., 2006; Harris et al., 2002, 2012; Kan et al., 2011), orthodontics (Kapila, Conley & Harrell, 2011; Mah, Huang & Choo, 2010; Mamatha et al., 2015; van Vlijmen et al., 2012), endodontics (Janner, Jeger, Lussi & Bornstein, 2011; Lofthag-Hansen, Huumonen, Grondahl & Grondahl, 2007; Patel, 2009), periodontology (Misch, Yi & Sarment, 2006; Vandenberghe, Jacobs & Yang, 2008; Walter, Kaner, Berndt, Weiger & Zitzmann, 2009), oral and maxillofacial surgery (Carter, Stone, Clark & Mercer, 2016; Kaeppler & Mast, 2012; Pohlenz et al., 2007; Popat, Richmond & Drage, 2010; Ren et al., 2016), and forensic dentistry (Ma et al., 2009; Yang, Jacobs & Willems, 2006).

CBCT provides numerous advantages for the depiction of bony structures compared to other dental (Cavalcanti, Haller & Vannier, 1999; Navarro Rde et al., 2013; Oliveira-Santos et al., 2011; Scarfe, Farman & Sukovic, 2006) and medical (Brisco, Fuller, Lee & Andrew, 2014; Kamburoglu, Murat, Yuksel, Cebeci & Paksoy, 2010; Patel, 2009; Suomalainen, Vehmas, Kortesniemi, Robinson & Peltola, 2008) imaging modalities. CBCT is a widely available, technically simple, low-cost, rapid acquisition radiographic procedure providing images with high spatial image resolution at relatively low radiation dose. In dental implant therapy, the use of CBCT facilitates diagnosis and improves treatment planning (Behneke, Burwinkel & Behneke, 2012; Bornstein et al., 2015; Chen, Lundgren, Hallstrom & Cherel, 2008; Worthington, Rubenstein & Hatcher, 2010).

CBCT units operate by directing a collimated cone-shaped X-ray beam through the head onto a flat panel or image intensifier detector and acquiring a series of planar basis images as a gantry connecting the two rotates around a fixed focal plane in a partial or full arc. Multiple planar basis images are reconstructed to generate volumetric data sets, which are processed by software to provide various inter-relational projections of the maxillofacial complex (De Vos, Casselman & Swennen, 2009; Scarfe, Levin, Gane & Farman, 2009). Sequential, contiguous, thin-slice cross-sectional images in multiplanar reconstructions (MPR) are usually created to depict the anatomic structures in flattened curved or linear transaxial planes, enabling linear measurements (Cavalcanti et al., 1999; Wikner et al., 2016). For most clinical applications, CBCT images are considered to enable highly accurate and reliable linear measurements (Raes, Renckens, Aps, Cosyn & De Bruyn, 2013; Scarfe & Farman, 2008; Scarfe et al., 2006; Tyndall et al., 2012; Yim, Ryu, Lee & Kwon, 2011). Nevertheless, the accuracy of reformatted CBCT images is affected by many factors. These include the characteristics of the machine (e.g., nominal resolution, image quality), radiation exposure (kV, mA, and the number of basis images), the software used for image reconstruction and dimensional measurement, patient motion artifacts, and the limitations of the clinician in interpretation (Halperin-Sternfeld, Machtei & Horwitz, 2014; Nikneshan et al., 2014).

The anatomic radiographic fidelity of bone structures and accuracy of linear measurements are crucial for basic preoperative implant planning, and even more so when applied in image-guided implant surgery (Nickenig & Eitner, 2007; Schneider, Marquardt, Zwahlen & Jung, 2009; Vieira, Sotto-Maior, Barros, Reis & Francischone, 2013). All guided surgery systems incorporate some degree of imprecision resulting in horizontal and particularly vertical deviations of the actual position of the implant compared to the presurgical virtual position (Laederach, Mukaddam, Payer, Filippi & Kuhl, 2016; Schneider et al., 2009; Vercruyssen et al., 2014, 2015, 2016).

As CBCT imaging is widely used to ascertain linear dimensions in various clinical dental applications, measurement accuracy must be defined. However, most in vivo clinical studies rarely quantify measurement accuracy, as this would often require an intervention to control the radiographic measurements (Feijo, Lucena, Kurita & Pereira, 2012). Thus, the objective of this systematic review was to identify, review, analyze, and summarize available evidence on the accuracy of linear measurements when using maxillofacial CBCT specifically in the field of implant dentistry.

2 | MATERIALS AND METHODS

2.1 | Search strategies

This systematic literature review was performed using a PICO (Patient or Population, Intervention, Control or Comparison, Outcome and Study design) framework (Table 1). The population was defined as patients or models (in vitro or experimental) specific for, but initially not limited to, implant placement. The intervention and comparison were described as the use of CBCT for the purpose of determining outcomes associated with the accuracy and reliability (repeatability/reproducibility) of linear measurements based on the data and the respective control values in patients or in vitro models/animals. The accuracy as measured in millimeters, kappa values, or correlation factors comparing test (CBCT measurements) with the control (patients, animals, or in vitro) were set as the outcome.

An electronic search without any time or language restrictions was undertaken in April 2017 initially in the National Library of Medicine database (Medline) through its online site (PubMed), followed by searches in the Cochrane, EMBASE, ScienceDirect, and ProQuest Dissertation and Thesis databases. Text terms as well as MeSH keywords specific to each part of the question were used for the searches (Table 1).

Gray literature was also searched and identified. Gray literature includes conference reports, technical reports, and working papers from government agencies, and university and scientific research groups that are not commercially published, and thus, they are usually not identified with conventional search strategies.

TABLE 1 Systematic search strategy for the focused question

Focused question	What is the accuracy of linear measurements using CBCT in daily clinical practice with special emphasis on implant dentistry?	
Search Strategy	Population	• Dental implants • Dentistry • Dental procedures • Dental care • Dental arch • in vivo • ex vivo • edentulous jaw • Mandible • Mandibular • Mandibular alveolar process • Maxillary • Maxilla
	Intervention or exposure	• cone beam computed tomography • tomography, X-ray computed tomography • CT scan • Volumetric CT • Volumetric computed tomography
	Comparison	• Linear measurement* • Measurement*
	Outcome	• Accuracy • Precision • Reproducibility of results • Dimensional measurement accuracy
	Search combinations	**PubMed** (((((linear measurement*) OR measurement*)) AND ((((((((((dental implants) OR dentistry) OR dental care) OR dental procedures) OR dental arch) OR in vivo[Title/Abstract]) OR ex vivo[Title/Abstract]) OR cadaver) OR edentulous) OR maxillary) OR mandible) OR mandibular) OR mandibular alveolar process)) AND (((((((cone beam computed tomography) OR tomography, x ray computed) OR Computed tomography scan) OR CT Scan) OR volumetric ct) OR volumetric computed tomography) OR linear measurement[Text Word])) AND ((((accuracy) OR precision) OR reproducibility of results) OR dimensional measurement accuracy) **EMBASE** "cone beam computed tomography"/exp OR "cone beam computed tomography" OR "X-ray tomography"/exp OR "X-ray tomography" OR volumetric AND computed AND tomography OR volumetric AND ct AND linear AND measurement* OR measurement* AND "accuracy"/exp OR "accuracy" OR "reproducibility"/exp OR "reproducibility" OR "dimensional measurement accuracy"/exp OR "dimensional measurement accuracy" AND "tooth implant"/exp OR "tooth implant" OR "tooth implantation" OR "dentistry"/exp OR "dentistry" OR "dental procedure"/exp OR "dental procedure" OR "tooth arch"/exp OR "tooth arch" OR "in vitro study" OR "ex vivo study" OR "edentulousness"/exp OR "edentulousness" OR "mandible"/exp OR "mandible" OR mandibular OR "alveolar bone"/exp OR "alveolar bone" OR "maxilla"/exp OR "maxilla" OR dental AND implant* **Cochrane** "dental implants or dentistry or dental care or dental arch or in vivo or ex vivo or edentulous or mandib* or maxill* in Title, Abstract, Keywords and linear measurement* or measurement* in Title, Abstract, Keywords and cone beam computed tomograph* or volumetric computed tomograph* or x-ray computed tomograph* in Title, Abstract, Keywords and precision or accuracy or reproducibility or dimensional meausrement accuracy in Title, Abstract, Keywords in Trials" **Proquest Dissertation & Thesis** (ab(dental implants) OR ab(dentistry) OR ab(dental care) OR ab(dental procedures) OR ab(dental arch) OR ab(in vivo) OR ab(ex vivo) OR ab(edentulous) OR ab(mandib?) OR ab(Maxilla?)) AND (ab(cone beam computed tomography) OR ab(cone beam ct) OR ab(tomography) OR ab(ct scan) OR ab(volumetric ct) OR ab(volumetric computed tomography) OR ab(x-ray computed tomography)) AND (ab(linear measurement?) OR ab(Measurement?)) AND (ab(accuracy) OR ab(precision) OR ab(reproducibility) OR ab(measurement accuracy))
Database search	Electronic	MEDLINE (Pubmed), Cochrane Library, Embase, ProQuest Dissertation & Thesis

2.2 | Inclusion criteria

Eligibility criteria were as follows:

- Studies performing linear CBCT measurements for quantitative assessment (e.g., height, width) of the alveolar bone at edentulous sites or measuring distances from anatomical structures related to implant dentistry. The studies should compare these values to clinical data (humans) or ex vivo and/or experimental (animal) findings from a "gold standard," that is, physical measurements using digital calipers and histomorphometry.
- Clinical studies with a sample size greater than 5.
- Experimental (animal) studies.
- In vitro studies using human cadavers or dry skulls measuring linear distances in alveolar bone or between fiducial placed markers.

The exclusion criteria were defined as:

- Studies with no control method for assessing the accuracy of linear measurements performed using CBCT.
- Studies comparing CBCT with other radiographic tests without an external control as gold standard.
- Case reports and case series with fewer than five patients.
- Linear measurements in disciplines unrelated to dental implant treatment (e.g., orthodontics, maxillofacial surgery, periodontology).
- Linear measurements on teeth or around teeth or implants.
- Review articles.

2.3 | Study selection process

Selection of studies was carried out in accordance with PRISMA guidelines. The initial search was formulated for maximal inclusion and high turnout. Two independent observers (G.F. and W.C.S.) analyzed the titles and abstracts of all identified reports. For the studies that appeared to meet the inclusion criteria or for which there were insufficient data in the titles and the respective abstracts to make a clear decision, the full texts of the articles were retrieved for further analysis. The final inclusion of the relevant full-text articles for evaluation was decided by consensus by the three observers (G.F., W.C.S., and M.B.).

2.4 | Data extraction process

Two reviewers (G.F. and W.C.S.) extracted relevant data according to the PICO framework using standardized data extraction tables. Extracted data included the following: author, title, year of publication, study model, nature of the "gold standard" measure, nature of other comparator measures, study design, CBCT parameters used, inter- and intra-observer reliability/agreement, and other outcome measures related to accuracy.

2.5 | Quality assessment

The quality of clinical studies was assessed using the National Institutes of Health "Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies" (https://www.nhlbi.nih.gov/health-pro/guidelines/in-develop/cardiovascular-risk-reduction/tools/cohort).

3 | RESULTS

3.1 | Study selection

The screening process is illustrated as a flowchart in Figure 1. The initial search yielded 2,516 titles. Of these, 458 were duplicates, resulting in 2,058 titles for further screening. The inclusion and exclusion criteria were applied and a total of 529 abstracts were considered for full-text selection, of which 40 were deemed as eligible. After full-text reading, 18 articles were further excluded for the following reasons (Table 2): (i) the measurements were taken on dentate jaws (Abboud, Guirado, Orentlicher & Wahl, 2013; Egbert, Cagna, Ahuja & Wicks, 2015; Halperin-Sternfeld et al., 2014; Maloney, Bastidas, Freeman, Olson & Kraut, 2011; Sun et al., 2011), (ii) both dentate and edentulous sites were studied, but separate data extraction for the edentulous sites was not possible (Fatemitabar & Nikgoo, 2010; Ganguly et al., 2011; Loubele, Guerrero, Jacobs, Suetens & van Steenberghe, 2007; Pertl, Gashi-Cenkoglu, Reichmann, Jakse & Pertl, 2013; Shokri & Khajeh, 2015; Suomalainen et al., 2008; Tarazona-Alvarez et al., 2014; Tarleton, 2014), (iii) no "gold standard" was used for the comparison as stated in the inclusion criteria (Li, Zhang, Liu, Fu & Zhang, 2016; Ritter et al., 2012; Vandenberghe et al., 2008; Yim et al., 2011), (iv) the measurements were taken using non-implant-related anatomical landmarks (Kamburoglu et al., 2011; Lascala, Panella & Marques, 2004; Tarazona-Alvarez et al., 2014).

In total, 22 studies were included in the final analysis. Of those, two were clinical (Eachempati et al., 2016; Luk, Pow, Li & Chow, 2011) and 20 ex vivo investigations. The ex vivo studies included 14 studies on dry jaws/skulls (Al-Ekrish, 2012; Al-Ekrish & Ekram, 2011; Al-Ekrish, Ekram, Al Faleh, Alkhader & Al-Sadhan, 2013; Alkan, Aral, Aral, Acer & Şişman, 2016; Freire-Maia et al., 2017; Kamburoglu, Kilic, Ozen & Yuksel, 2009; Luangchana, Pornprasertsuk-Damrongsri, Kiattavorncharoen & Jirajariyavej, 2015; Neves, Vasconcelos, Campos, Haiter-Neto & Freitas, 2014; Pena de Andrade, Valerio, de Oliveira Monteiro, de Carvalho Machado & Manzi, 2016; Sheikhi, Dakhil-Alian & Bahreinian, 2015; Torres, Campos, Segundo, Navarro & Crusoe-Rebello, 2012; Vasconcelos, Neves, Moraes & Freitas, 2015; Veyre-Goulet, Fortin & Thierry, 2008; Waltrick et al., 2013) and six cadaver studies (Ganguly et al., 2016; Gerlach et al., 2013, 2014; Kobayashi, Shimoda, Nakagawa & Yamamoto, 2004; Loubele et al., 2008; Santana et al., 2012).

As the methodology of the included studies as well as the extracted data was inhomogeneous, a meta-analysis could not be carried out and thus only a descriptive analysis performed.

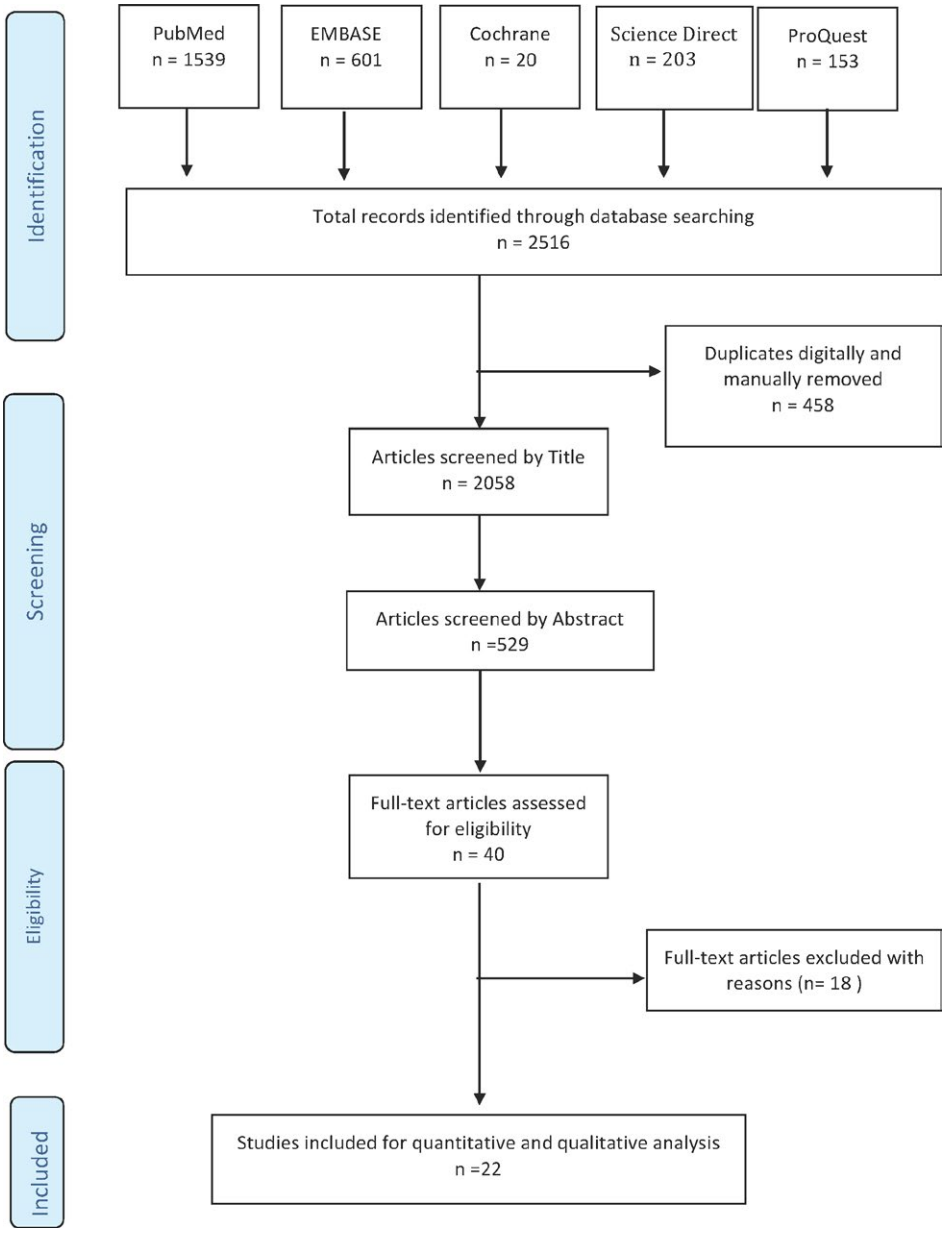

FIGURE 1 Flowchart showing the screening process

3.2 | Study characteristics

The key information of the selected studies such as study design, aim of the study, sample size, reference standards (comparator), methodology of assessment, representative outcomes, and major conclusions is presented in Table 3.

The two included clinical studies assessed edentulous sites of patients prior to dental implant treatment (Eachempati et al., 2016; Luk et al., 2011). The majority of the selected studies used dry human mandibles as the sample (Al-Ekrish, 2012; Alkan et al., 2016; Freire-Maia et al., 2017; Kamburoglu et al., 2009; Kobayashi et al., 2004; Neves et al., 2014; Pena de Andrade et al., 2016; Sheikhi et al., 2015; Torres et al., 2012; Vasconcelos et al., 2015; Waltrick et al., 2013). Two studies used both the maxilla and mandible of dry skulls (Abboud et al., 2013; Al-Ekrish & Ekram, 2011; Luangchana et al., 2015), and one study used only three dry maxillae (Veyre-Goulet et al., 2008). With regard to cadaver studies, only one study scanned both jaws for the measurements (Ganguly et al., 2016), four studies used mandibles (Gerlach et al., 2013, 2014; Kobayashi et al., 2004; Santana et al., 2012), and one study used a cadaver maxilla only (Loubele et al., 2008).

Seven of the ex vivo studies placed the dry jaws/skulls in a container with water to simulate the effects of soft tissue for CBCT imaging (Alkan et al., 2016; Freire-Maia et al., 2017; Neves et al., 2014; Sheikhi et al., 2015; Torres et al., 2012; Vasconcelos et al., 2015; Veyre-Goulet et al., 2008), while Luangchana et al. covered the jaws entirely in acrylic resin for that purpose (Luangchana et al., 2015).

TABLE 2 Reason for exclusion of full-text articles

Publication (author, year)	Reason for exclusion
Li et al. (2016)	Measurements performed on models printed using a CBCT data
Shokri & Khajeh (2015)	Does not specify or identify, which of the measured areas were edentulous
Egbert et al. (2015)	Uses a single dentate cadaveric mandible
Tarleton (2014) (thesis)	Does not discriminate between samples (dentate and partially dentate hemisected dry mandibles)
Tarazona-Alvarez et al. (2014)	Does not discriminate between dentate and edentulous; uses surgical anatomical landmarks
Halperin-Sternfeld et al. (2014)	Uses dentate fresh pig mandibles
Pertl et al. (2013)	Does not specify or identify which of the measured areas were edentulous
Abboud et al. (2013)	Uses a dentate mandible only; does not specify if edentulous sites are measured
Ritter et al. (2012)	No gold standard used for evaluating accuracy
Yim et al. (2011)	No gold standard used (GP markers of known length and calibration as reference); sites for linear measurements not specified (compares magnification of OPG and CBCT)
Sun et al. (2011)	Uses a dentate porcine maxillae
Maloney et al. (2011)	Uses dentate dry human mandibles
Kamburoglu et al. (2011)	Measures distances between anatomical landmarks. Does not specify implant dentistry-related distances (e.g., mental foramen–mental foramen)
Ganguly et al. (2011)	Uses dentulous and edentulous cadaver heads; does not specify if edentulous areas are measured
Fatemitabar & Nikgoo (2010)	Measurements performed on dentate and edentulous segments; does not specify if edentulous areas are measured
Suomalainen et al. (2008)	Only one partially edentulous human dry mandible used; does not specify which edentulous areas are measured
Loubele et al. (2007)	Uses partially and fully edentulous dry mandibles; does not specify which edentulous areas are measured
Lascala et al. (2004)	Does not specify implant dentistry-related distances (e.g., mental foramen–mental foramen)

A wide spectrum of CBCT units and acquisition parameters were used to acquire volumes (Table 4). Some authors investigated the effect of various exposure, acquisition, or display factors while others compared accuracy of CBCT to MSCT.

3.3 | Aim of the included studies

For many studies, the stated objectives were often at variance from the methodology and results presented. Of the authors that aimed solely to evaluate the accuracy of CBCT, some used one single machine and fixed acquisition parameters (Gerlach et al., 2013, 2014; Kamburoglu et al., 2009; Kobayashi et al., 2004; Veyre-Goulet et al., 2008), while others evaluated the effect of different scan parameters (Al-Ekrish, 2012; Ganguly et al., 2016; Neves et al., 2014; Torres et al., 2012; Waltrick et al., 2013), different reconstruction software (Vasconcelos et al., 2015), or different monitors (Al-Ekrish et al., 2013) on linear accuracy. Furthermore, in several studies the authors' primary objective was to compare the accuracy of CBCT with other radiographic or clinical diagnostic tests (Al-Ekrish & Ekram, 2011; Alkan et al., 2016; Eachempati et al., 2016; Freire-Maia et al., 2017; Loubele et al., 2008; Luangchana et al., 2015; Luk et al., 2011; Pena de Andrade et al., 2016; Santana et al., 2012; Sheikhi et al., 2015).

3.4 | Reference standards (comparators for linear CBCT measurements)

For the ex vivo studies, 17 of the 20 utilized histologic sectioning of the jaws followed by physical measurements with a digital caliper as a reference standard. Santana et al. (2012) used a combination of an analogue and a digital caliper on cadaver dissections to establish to extension of the anterior loop of the mental branch relative to the mental foramen. The accuracy of these measuring instruments was specified in only seven studies: Three studies described a 0.01 mm accuracy of the caliper used (Loubele et al., 2008; Sheikhi et al., 2015; Waltrick et al., 2013) and four described an accuracy of 0.02 mm (Al-Ekrish, 2012; Al-Ekrish & Ekram, 2011; Al-Ekrish et al., 2013; Luangchana et al., 2015). The two studies by Gerlach et al. (2013, 2014) on fresh frozen cadavers used histomorphometry as the gold standard.

TABLE 3 General characteristics of the included studies with focus on comparison of linear measurements using CBCT vs gold standard (n = 22) [In PDF format, this table is best viewed in two-page mode]

Author (year)	Sample	Aim of study	Gold standard	Sample size
Freire-Maia et al. (2017)	Eight dry mandibles (ex vivo)	Compare the accuracy of linear measurements of 64-detector MSCT and CBCT	Sectioning+ digital caliper (DC)	Six sites on each sample (molar, retromolar, ramus); 48 measurements in total
Pena de Andrade et al. (2016)	Six dry mandibles (ex vivo)	Compare the accuracy of linear measurements of 64-detector MSCT and CBCT	Sectioning+ digital caliper	Eight sites on each sample (incisor, canine, premolar, molar); 48 measurements
Ganguly et al. (2016)	Four cadaver heads (maxilla and mandible) (ex vivo)	Compare the effect of FOV and voxel size on the accuracy of linear measurements of CBCT	Sectioning+ digital caliper	Two edentulous sites on each sample in both dental arches (premolar, molar); 28 measurements
Eachempati et al. (2016)	Edentulous sites of 12 patients (in vivo)	Compare ridge mapping and panoramic radiographs with CBCT for implant site assessment	Ridge mapping (RM)	37 edentulous sites (anterior maxilla, posterior maxilla, posterior mandible); 37 measurements
Alkan et al. (2016)	Five dry mandibles/ five dry maxillae (ex vivo)	Compare the linear measurement accuracy of CBCT, panoramic radiography, periapical radiography, and digital photography in evaluating alveolar bone height and extraction socket dimensions	Sectioning+ digital caliper with loupe magnification (3.5×) (DC + L)	Anterior, premolar, and molar sites; buccal–lingual and mesiodistal alveolar extraction socket dimensions; 255 measurements
Vasconcelos et al. (2015)	Eight dry edentulous mandibles (ex vivo)	Comparing the accuracy of linear alveolar bone height measurements of three different commercial dental software packages for CBCT	Sectioning+ digital caliper	Five edentulous sites (incisor canine, premolar, first molar, second molar); 80 measurements
Sheiki et al. (2015)	Three dry edentulous mandibles (ex vivo)	Compare the linear measurement accuracy of tangential projection (TP) and CBCT in evaluating alveolar bone height and width	Sectioning+ digital caliper	Three edentulous sites (midline lateral incisor, canine); 30 measurements
Luangchana et al. (2015)	Six partially or fully edentulous skulls (ex vivo)	Compare the linear measurement accuracy of CBCT and digital panoramic radiographs in evaluating alveolar bone height	Sectioning+ digital caliper	Six edentulous sites (maxillary and mandibular incisor, mandibular canine, maxillary and mandibular premolar and molar); 48 measurements

(Continues)

TABLE 3 (additional columns)

Accuracy Index	Representative outcomes	Key inference
Mean differences of the distance between the mandibular cortical bone and the mandibular canal (MC) between DC/CBCT at the different sites measured	Ramus: −0.16 to 0.11 mm Retromolar: −0.01 to 0.21 mm Molar: −0.16 to 0.19 mm	No significant difference* CBCT and MSCT are highly accurate to measure the location of the mandibular canal in relation to the adjacent cortical bone of the mandible
Mean measurements for height and width of alveolar ridge	Difference caliper/CBCT −0.08 to −0.23 mm (height) −0.18 to −0.22 mm (width)	No significant difference* CBCT and MSCT are accurate to measure the height and width of alveolar bone
Mean measurements and absolute differences with three scan protocols: • large FOV/0.3 mm voxel • large FOV/0.2 mm voxel • small FOV/0.16 mm voxel for height and width of alveolar ridge	Mean absolute difference: 1.10 ± 1.3 mm (0.3 mm voxel) 1.2 ± 1.5 mm (0.2 mm voxel) 1.1 ± 1.4 mm (0.16 mm voxel)	No statistical difference* between the physical measurements and measurements from any of the CBCT protocols applied using different voxel sizes
Absolute difference among the three protocols		No statistical difference among protocols* CBCT measurements are accurate to measure the height and width of alveolar bone. Smaller voxel sizes do not result in greater accuracy of linear measurements
Correlation of width of alveolar crest between RM and CBCT (Pearson's *r*)	0.53	Moderate correlation between RM and CBCT for measurements of width of alveolar crest
Mean/median difference of width of alveolar crest between RM and CBCT	1.2/0.34 mm	CBCT (alveolar crest) measurements overestimate RM
Correlation of alveolar crest measurements between RM and CBCT (Pearson's *r*)	94.6% of measurement within 95% CI	
Correlation (Spearman's)	Extraction socket: Buccolingual: 0.782 ($p < 0.05$) Mesiodistal: 0.983 ($p < 0.01$)	High correlation between CBCT and DC + L for extraction socket dimensions
Mean difference between DC + L/CBCT	Buccolingual (mm) 6.77 ± 1.15/6.63 ± 1.35 ($p < 0.05$) Mesiodistal (mm) 4.72 ± 1.23/4.73 ± 1.12 ($p < 0.001$)	The difference of the buccolingual measurement was significant (CBCT < DC + L)
Mean difference of the distance between the cortical bone and the MC for three software packages S1, OnDemand S2, KDIS 3D S3, XoranCat	S1: −0.11 mm S2: −0.14 mm S3: 0.25 mm	No significant differences between the measurements with the three software packages and the gold standard or among them All tested dental software packages provide accurate linear alveolar bone height measurements
Agreement CBCT/DC (ICC)	Bone height: CBCT 0.89 Bone width: CBCT 0.91	There was a high agreement among physical measurements, CBCT, and TP
Mean error	Height: 0.06 ± 0.05 mm Width: 0.04 ± 0.03 mm	There was a slight underestimation of dimensions in the CBCT results
Correlation CBCT/DC (Paired sample correlation) Mean difference of measurements CBCT/DC for five CBCT scan protocols (voxel size 0.125 mm/0.16 mm/0.25 mm/0.2 mm/0.3 mm) Absolute error (mm) for all five protocols Absolute percentage error for all five protocols	>0.997 Maxilla: −1.06 ± 1.0 to −1.23 ± 0.81 mm Mandible: −0.24 ± 0.46 to −0.55 ± 0.61 mm Maxilla 1.14 ± 0.80 to 1.27 ± 0.89/ Mandible 0.39 ± 0.27 to 0.66 ± 0.47 Maxilla: 10.74% to 11.81% Mandible: 2.77% to 4.84%	The correlation was significant for all voxel sizes CBCT and PR measurements underestimate the actual distance. No significant difference between any protocol and the physical measurements. Machine or voxel size does not affect measurement accuracy

(Continues)

TABLE 3 (Continued) [In PDF format, this table is best viewed in two-page mode]

Author (year)	Sample	Aim of study	Gold standard	Sample size
Neves et al. (2014)	16 dry edentulous hemimandibles (ex vivo)	Evaluate the effect of CBCT scan mode for preoperative dental implant measurements	Sectioning+ digital caliper	Five edentulous sites (incisor, canine, premolar, first molar, second molar); 64 measurements
Gerlach et al. (2014)[a]	One dentate and one edentulous fresh frozen cadaver head (ex vivo)	Evaluate the linear measurement accuracy of CBCT in evaluating the size and position of the MC	Histological sections (HS)	Eight sites (second molar, second premolar); 46 measurements (24 for the edentate cadaver)
Waltrick et al. (2014)	12 dry hemimandibles with edentulous posterior ridges (ex vivo)	Verify the accuracy of linear measurements of alveolar bone and width and analyze the visibility of the MC on CBCT images obtained using different voxel sizes	Sectioning+ digital caliper	Three edentulous sites (second premolar, first molar, and second molar); 108 measurements
Gerlach et al. (2013)[a]	One dentate and one edentulous fresh frozen cadaver head (ex vivo)	Compare the linear measurement accuracy of CBCT in evaluating alveolar bone dimensions and cortical layer thickness	Histological sections	Four sites in the maxilla (second molar, second premolar, canine, lateral incisor), three sites in the mandible (second molar, second premolar, lateral incisor); 46 measurements (24 for the edentate)
Al-Ekrish et al. (2013)	Five edentulated dry human skulls (four maxillae, five mandibles) (ex vivo)	Determine the effect of the use of three LCD monitors on the linear measurement accuracy of CBCT in evaluating alveolar bone dimensions	Sectioning+ digital caliper	Three sites (incisor, canine–premolar, molar); 48 measurements
Torres et al. (2012)	Eight dry fully edentulous human mandibles (ex vivo)	Compare the effect of different voxel size on the linear measurement accuracy of CBCT in evaluating alveolar bone dimensions	Sectioning+ digital caliper	Three sites (incisor, premolar, molar); 96 measurements
Santana et al. (2012)	12 cadavers (six dentate/six edentulous) (ex vivo)	Compare the degree of visibility and linear measurement accuracy of CBCT and STL model in identifying and measuring the anterior loop length of the mental nerve	Anatomic dissection+ Digital and analog caliper	23 mental nerve plexus; 115 measurements

(Continues)

TABLE 3 (additional columns - continued)

Accuracy Index	Representative outcomes	Key inference
Correlation CBCT/DC (Wilcoxon signed-rank test)	Incisor P1/P2: 0.23/0.11 Canine P1/P2: 0.95/0.45 Premolar p1/P2: 0.48/0.64 1st molar P1/P2: 0.06/0.23 1st molar MC height, P1/P2: 0.31/0.51	No statistically significant difference between CBCT and DC for both scan modes except for 2nd molar in full scan (360°) mode
	2nd molar P1/P2: 0.02*/0.36 2nd molar MC height, P1/P2: 0.75/0.15	Half-scan mode (180°) provides same accuracy at 50% dose reduction
Mean difference for measurements between alveolar crest and lower border of mandible or MC for two CBCT scan protocols (P1, 360°; P2, 180°)	Incisor P1/P2, −0.2/−0.2 mm Canine P1/P2, 0.1/0.3 mm PM P1/P2, −0.1/−0.0 mm First molar, P1/P2, −0.2/0.1 mm Second molar, P1/P2, −0.4/−0.2 mm	
Mean differences CBCT/HS for the six different sites	Range: −0.14 ± 0.16 to 0.35 ± 0.25 mm	No statistically significant difference except the distance center of MC to the buccal margin of the mandible ($p = 0.006$)
Mean difference between maximum and minimum diameter of MC	−0.52 ± 0.26 mm to 0.02 ± 0.33 mm	To be clinically safe, an extra 0.74 mm should be added when determining the diameter of the MC
Correlation (Pearson's *r*)	>0.998	Excellent agreement between CBCT and direct measurements
Absolute mean error between three CBCT scan protocols (voxel size 0.2 mm/0.3 mm/0.4 mm)	Overall: 0.23 ± 0.20 mm Overall height: 0.18 ± 0.14 mm Overall width: 0.33 ± 0.25 mm	All measurements are accurate (ME < 1 mm) Underestimation occurs in 60.2% of measurements
Visibility rated on scale of 3 (visible) to 0 (not visible) for three CBCT scan protocols	0.2 mm: 86.1% scored 3 0.3 mm: 70.8% scored 3 0.4 mm: 55.6% scored 3	Increasing voxel resolution increases visibility (but NSD)
		A voxel size of 0.3 mm is a good compromise between image quality and radiation optimization
Absolute and relative (%) mean difference for alveolar height and width and mandibular border cortical thickness	Height edentulous 0.16 ± 0.15 mm Width edentulous 0.31 ± 0.22 mm	The edentate measurements were statistically significant for all distances
	Cortical thickness range edentulous, 0.49 ± 0.19 mm to 0.63 ± 0.1 mm	All measurements overestimate actual dimensions up to 4.4% but are <1 mm
		All measurements overestimate cortical thickness from 32.1% to 82.6%
Absolute mean error of measurement of alveolar height and width (combined) for three CBCT viewing monitors (M1, workstation; M2, laptop 1; M3, laptop 2)	M1: 0.55 ± 0.18 mm; M2: 0.61 ± 0.1 9 mm; M3: 0.68 ± 0.22 mm	The measurement error from all three display monitors was significantly different from the direct measurements ($p < 0.001$)
		No significant difference among the three tested devices
% mean error of measurement of alveolar bone dimensions (V, vertical; H, horizontal) for four CBCT scan protocols (voxel size: 0.2 mm/0.25 mm/0.3 mm/0.4 mm)	Mean/Median: 0.2 mm: 12.65%/8.54% 0.25 mm 12.2%/7.46% 0.3 mm: 12.18%/7.46% 0.4 mm: 13.62%/8.38%	No significant difference among the four protocols. All measurements are accurate (ME < 1 mm)
Mean difference DC/CBCT	Range 0.68–0.72 for the four protocols	Most measurements underestimated the real values
Mean measurement (mm) of the anterior loop length of the mental nerve using two protocols (T, with radiopaque tracer; NT, without radiopaque tracer) for CBCT and STL models	Caliper: 1.64 ± 1.37 mm CBCT NT: 1.6 ± 1.44 mm CBCT T: 1.59 ± 1.38 mm	No significant difference between the anterior loop length of the mental nerve measurements and CBCT with ($p = 0.332$) or without tracer ($p = 0.102$)
		CBCT is a prerequisite in identifying and measuring the anterior loop length

(Continues)

TABLE 3 (Continued) [In PDF format, this table is best viewed in two-page mode]

Author (year)	Sample	Aim of study	Gold standard	Sample size
Al-Ekrish (2012)	Five edentulous dry human skulls (four maxillae, five mandibles) (ex vivo)	Evaluate the effect of reducing number of basis images (low dose) on the linear measurement accuracy of CBCT in evaluating alveolar bone dimensions	Sectioning+ digital caliper	Three sites (incisor, canine–premolar, molar); 83 measurements
Luk et al. (2011)	14 partially dentate patients (in vivo)	Compare the linear measurement accuracy of RM and CBCT in evaluating alveolar crestal bone dimensions	Ridge mapping (RM)	21 alveolar potential implant sites (posterior and anterior maxilla, posterior mandible); 147 measurements
Al-Ekrish & Ekram (2011)	Five edentulous dry human skulls (four maxillae, five mandibles) (ex vivo)	Compare the accuracy of linear measurements of 16-detector MSCT and CBCT	Sectioning+ digital caliper	Three sites (incisor, canine–premolar, molar); 80 measurements
Kamburoglu et al. (2009)	Six dry human hemimandibles (ex vivo)	Compare the accuracy of linear measurements of CBCT in evaluating bone dimensions adjacent to the MC	Sectioning+ digital caliper	Seven sites from the anterior margin of the third molar to the anterior margin of the second premolar; 84 measurements
Veyre-Goulet et al. (2008)	Three dry maxillae (ex vivo)	Compare the accuracy of linear measurements of CBCT in evaluating alveolar bone height and width in maxillary edentulous regions	Sectioning+ digital caliper	14 anatomic sites; 28 measurements
Loubele et al. (2008)	One edentulous cadaver maxilla (ex vivo)	Compare the accuracy of linear measurements of 16-detector, four detector MSCT and CBCT in evaluating alveolar bone width	Holes drilled in the position of the markers+ digital caliper	Eight sites around maxillary arch; eight measurements
Kobayashi et al. (2004)	Five cadaver mandibles (ex vivo)	Compare the accuracy of linear measurements of MSCT and CBCT in evaluating alveolar bone height	Sectioning+ digital caliper	Seven sites (right and left molar, right and left premolar, right and left canine, midline, left canine); 35 measurements

CBCT, cone beam computed tomography; DC, digital caliper; L, loupe; MC, mandibular canal; MSCT, multislice computed tomography; RM, ridge mapping; STL, stereolithography; NSD, no significant difference; ICC, intraclass correlation coefficient.
*$p < 0.05$.
[a]Part of the same study.

Both clinical studies used alveolar crestal ridge mapping as a reference (Eachempati et al., 2016; Luk et al., 2011). Eachempati et al. (2016) did not specify the instruments used for these measurements, and Luk et al. (2011) mentioned using a steel ruler with 0.5-mm accuracy.

3.5 | Assessment of accuracy

Overall, there was no consistency in the use of an accuracy index between the gold standard and the linear measurements using CBCT in the identified studies (Table 3).

The mean difference was used in 12 studies (Alkan et al., 2016; Eachempati et al., 2016; Freire-Maia et al., 2017; Gerlach et al., 2014; Loubele et al., 2008; Luangchana et al., 2015; Luk et al., 2011; Pena de Andrade et al., 2016; Santana et al., 2012; Torres et al., 2012; Vasconcelos et al., 2015; Veyre-Goulet et al., 2008), two studies presented the mean absolute difference (Ganguly et al., 2016; Gerlach et al., 2013), and one study also presented the mean relative difference as a percentage (Gerlach et al., 2014).

The correlation between CBCT and the reference standard used was presented in six of the included studies (Alkan et al., 2016; Eachempati et al., 2016; Kamburoglu et al., 2009; Luangchana et al., 2015; Neves et al., 2014; Waltrick et al., 2013), and two assessed agreement (Eachempati et al., 2016; Sheikhi et al., 2015). The mean measurement error in millimeters between the two values was calculated in two studies (Kobayashi et al., 2004; Sheikhi et al., 2015), one study presented the absolute error of the measurements in millimeters (Luangchana et al., 2015), four studies evaluated the mean absolute error in millimeters (Al-Ekrish, 2012; Al-Ekrish & Ekram,

TABLE 3 (additional columns - continued)

Accuracy Index	Representative outcomes	Key inference
Absolute mean error CBCT/direct (height and width) for three acquisition protocols (40s, 20s, 7s) overall	40s: 0.50 ± 0.47 mm, 20s: 0.46 ± 0.46 mm 07s: 0.51 ± 0.47 mm	The absolute mean errors were statistically significant for the entire sample size, even though submillimetric
Absolute error of height measurements at sites containing the inferior dental canal	40s: 0.43 ± 0.49 mm 20s: 0.53 ± 0.49 mm 7s: 0.52 ± 0.52 mm	No statistically significant difference among the protocols
Frequency of absolute ME measurements >0.5 and 1.0 mm	Frequency >0.5 mm/>1 mm: 40 s: 36.1%14.5%, 20s: 41%/12.1%, 07s: 36.1%/16.9%	Reducing the CBCT exposure time number of basis images does not affect the measurement accuracy at implant sites
		CBCT significantly (>1 mm) overestimates measurements 12.1% to 16.9% of the time
Difference CBCT/RM	Mean: 0.4 ± 0.5 mm Range: −0.9 to 2.9 mm	CBCT > RM (p = 0.001)
		CBCT overestimates RM by 0.3 to 0.5 mm
Absolute mean error CBCT/direct of measurement of alveolar height and overall (height and width)	Overall: 0.48 ± 0.44 mm	Statistically significant for the entire sample size and separately height/width/maxilla/mandible
Frequency of absolute mean error >0.5 and 1.0 mm	>0.5 mm/>1 mm: 33.3%/12.5%	CBCT significantly (>1 mm) overestimates measurements in 12.5% of the times
Correlation (ICC) Mean difference (mm) of six dimensions (mandibular width; mandibular height; superior/inferior/buccal/lingual to the MC) per site	Observer1: 0.61–0.93 Observer2: 0.4–0.95 (Distance MC-top of ridge ICC>0.9. ICC 0.4&0.61 was only for the distance between the canal and the lingual margin)	The mean/median differences were "clinically insignificant"—but no statistical analysis was performed
Difference in alveolar height and width	Height range: 0.05 to 0.6 mm, Width range: 0.00 to 0.3 mm	No clinically significant difference (however, no statistics performed)
		CBCT provides clinically acceptable data, but in general with an overestimation of bone height and width
Difference CBCT/direct	Accuracy −0.09 ± 1.64 mm	NSD between physical and radiographic measurements or between CBCT/MSCT
Absolute error CBCT/direct	Mean 0.22 ± 0.15 mm Range 0.01 to 0.65 mm/	Maximum error <1 mm
Percentage of absolute error	Mean: 1.4% Range: 0.1%–5.2%	Mean error of CBCT significantly less than spiral CT

2011; Al-Ekrish et al., 2013; Waltrick et al., 2013), and three studies reported on the absolute percentage error (Kobayashi et al., 2004; Luangchana et al., 2015; Torres et al., 2012).

3.6 | Outcomes of assessment of accuracy

The majority of the studies reported submillimeter differences between CBCT and "gold standard" measurements without a statistically significant difference. Nevertheless, the range of differences between these measurements often exceeded the 1-mm threshold. Eachempati et al. (2016) reported a mean difference of 1.2 mm, but no statistical analysis was performed. Similarly, Veyre-Goulet et al. (2008) reported a range of differences from 0.03 to 0.6 mm, indicating that these differences were "not clinically significant," but without further analysis. However, in studies where a similar difference range was reported, these differences were determined to be statistically significant (Gerlach et al., 2013, 2014; Luk et al., 2011).

In studies that assessed absolute error (millimeters) between the two measurements, most authors reported low values ranging from 0.04 mm (Sheikhi et al., 2015) to 0.68 mm (Al-Ekrish et al., 2013) with the exception of Luangchana et al. (2015), who reported errors of 1.14 to 1.27 mm for the maxilla (Luangchana et al., 2015). Al-Ekrish and Ekram (2011) (Al-Ekrish, 2012; Al-Ekrish & Ekram, 2011; Al-Ekrish et al., 2013) reported that absolute errors of this magnitude were statistically significant. Luangchana et al. (2015) and Torres et al. (2012) both reported significant differences between the gold standard and CBCT (Luangchana et al., 2015; Torres et al., 2012),

TABLE 4 Summary of the CBCT units used in the included studies (n = 22) and reported exposure and acquisition parameters

Study/year	Unit (make/model)	Voxel size (mm^3)	FOV (H × W) (cm)	Voltage (kV)	Current (mA)	Scan time (s)	Slice thickness (mm)	Viewing software
Freire-Maia et al. (2017)	i-CAT Next Generation[a]	0.2	13 × 16 (Large)	120	7	20	–	–
Pena de Andrade et al. (2016)	i-CAT[a]	–	–	–	–	–	–	–
Ganguly et al. (2016)	i-CAT Classic[a]	0.2	13 × 16 (Large)	–	–	20	–	XoranCat[b]
		0.3	13 × 16 (Large)	–	–	20	–	XoranCat[b]
	Promax 3D[c]	0.16	5 × 8 (Small)	84	14	12	–	Romexis 3.0[c]
Eachempati et al. (2016)	Promax 3D[c]	0.16	5 × 8 (Small)	90	14	–	–	Romexis 3.0[c]
Alkan et al. (2016)	i-CAT Next Generation[a]	0.3	–	120	5	9.6	0.25	ImageJ[d]
Vasconcelos et al. (2015)	i-CAT Next Genera tion[a]	0.2	–	120	37.07	26.9	–	XoranCat[b] OnDemand3D[e] KDIS3D[f]
Sheikhi et al. (2015)	Galileos Compact[g]	–	–	–	–	14	–	–
Luangchana et al. (2015)	3D Accuit omo 170[h]	0.125	–	–	–	–	–	i-Dixel[h]
		0.16	–	–	–	–	–	i-Dixel[h]
		0.25	–	–	–	–	–	i-Dixel[h]
	CS 9500[f]	0.2	–	–	–	–	–	CS 3D[f]
		0.3	–	–	–	–	–	CS 3D[f]
Neves et al. (2014)	i-CAT Next Genera tion[a]	0.2	–	120	20.27	14.7 (180°)	–	OnDemand3D[e]
		0.2	–	120	37.07	26.9 (360°)	–	OnDemand3D[e]
Gerlach et al. (2014)	i-CAT[a]	0.4	22 × ? (Large)	120	1.2	40	–	Procera[i]
Waltrick et al. (2013)	- i-CAT[a]	0.4	8 × ?	120	3–8	20	1.2	i-CAT Vision[a]
		0.3	8 × ?	120	3–8	20	1.2	i-CAT Vision1
		0.2	8 × ?	120	3–8	40	1.2	i-CAT Vision[a]
Gerlach et al. (2013)	i-CAT[a]	0.4	22 × ?	120	1.2	40	–	Procera[i]
Al-Ekrish et al. (2013)	Iluma[j]	0.29	19 × 24 (Large)	120	3.8	40	–	Vision 3-D[j]
Torres et al. (2012)	i-CAT[a]	0.2	6 × 16	120 kV	46.72	40	–	XoranCat[b]
		0.25	6 × 16	120	46.72	40	–	XoranCat[b]
		0.3	6 × 16	120	23.87	40	–	XoranCat[b]
		0.4	6 × 16	120	23.87	40	–	XoranCat[b]
Santana et al. (2012)	i-CAT[a]	–	–	120	24	20	–	–
Al-Ekrish (2012)	Iluma[j]	0.29	19 × 24 (Large)	120	3.8	7	0.29	Vision 3-D[j]
		0.29	19 × 24 (Large)	120	3.8	20	0.29	Vision 3-D[j]
		0.29	19 × 24 (Large)	120	3.8	40	0.29	Vision 3-D[j]

(Continues)

TABLE 4 (Continued)

Study/year	Unit (make/model)	Voxel size (mm^3)	FOV (H × W) (cm)	Voltage (kV)	Current (mA)	Scan time (s)	Slice thickness (mm)	Viewing software
Luk et al. (2011)	i-CAT Classic[a]	0.4	–	120	3–8	–	–	i-CAT Vision[a]
Al-Ekrish & Ekram (2011)	Iluma[j]	0.29	19 × 24 (Large)	120	3.8	39.9	0.29	Vision 3-D[j]
Kamburoglu et al. (2009)	Iluma Ultra[k]	0.2	–	120	3.8	40	–	Vision 3-D[k]
Veyre-Goulet et al. (2008)	Newtom 9000[l]	–	–	85	7	70	–	EasyGuide[m]
Loubele et al. (2008)	Accuitomo 3D[h]	0.125	–	70	74	17.5	–	SPM[n]
Kobayashi et al. (2004)	Dental 3D-CT[o]	0.117	4.27 × 3 (Small)	–	–	–	0.117	Express Vision[p]

s: seconds; mm: millimeters; kV: kilovoltage; mA: milliamperes; H: height of scan volume; W: maximum diameter of scan volume.
[a]Imaging Sciences International, Hatfield, PA, USA.
[b]Xoran Technologies LLC, Ann Arbor, MI, USA.
[c]Planmeca USA Inc., Roselle, IL, USA.
[d]United States National Institutes of Health, Bethesda, MD, USA.
[e]CyberMed Inc., Seoul, South Korea.
[f]Kodak Dental Systems, Carestream Health, Rochester, NY, USA.
[g]Sirona Dental Systems GMBH, Bensheim, Germany.
[h]J. Morita Manufacturing Corp., Kyoto, Japan.
[i]NobelGuide, Nobel Biocare, Göteborg, Sweden.
[j]Imtek Imaging, 3M Company, St. Paul, MN, USA.
[k]Imtec Imaging, Ardmore, OK, USA.
[l]Quantitative Radiology, Verona, Italy.
[m]Keystone Dental, Inc., Burlington, MA, USA.
[n]Statistical Parametric Mapping, Wellcome Department of Imaging Neuroscience London, UK.
[o]PSR 9,000 prototype, Asahi Roentgen, Kyoto, Japan.
[p]Zio Software, Tokyo, Japan.

TABLE 5 Descriptive analysis of the outcomes regarding assessment of reiliability (repeatability/reproducibility) in the studies included

Study	Method of assessment	Intra-examiner	Interexaminer
Freire-Maia et al. (2017)	ICC	1.0–0.961[p]	0.923–0.997[r]
Pena de Andrade et al. (2016)	NR	—	—
Ganguly et al. (2016)	Bland and Altman/ICC	0.978–0.985[r]	0.961[r]
Eachempati et al. (2016)	NR	—	—
Alkan et al. (2016)	ICC	0.995 (95% CI: 0.991–0.998)[r]	0.989 (95% CI: 0.979–0.995)[r]
Vasconcelos et al. (2015)	ICC	0.98–0.99[r]	1 examiner
Sheikhi et al. (2015)	ICC	0.78–0.8[r]	0.78–0.97[r]
Luangchana et al. (2015)	ICC/Cronbach's alpha	0.996–1.0[r]/NR	0.991–1.0[r]/NR
Neves et al. (2014)	ICC	0.96–0.98[r]	0.98[r]
Gerlach et al. (2014)	ICC	NR	0.93[r]
Waltrick et al. (2013)	Pearson correlation coefficient (*r*)	NR	0.9983–0.9991[r]
Gerlach et al. (2013)	*SD*/Pearson correlation coefficient (*r*)	(0.03–0.11 mm)[p], (0.13–0.21mm)[r]	0.96[r]
Al-Ekrish et al. (2013)	Pearson correlation coefficient (*r*)/ Cronbach's alpha	(1.000)[p], (0.994–0.998/0.997–0.999)[r]	(0.993–0.99/0.993–0.998)[r]
Torres et al. (2012)	Pearson correlation coefficient (*r*)	(0.831 to 0.995)[r], 0.987[p]	1 examiner
Santana et al. (2012)	Cronbach's alpha	NR	1 examiner
Al-Ekrish (2012)	Pearson correlation coefficient (*r*)/ Cronbach's alpha	(0.99)[p], (0.993–0.996/0.996–0.998)[r]	(0.994–0.98/0.997–0.999)[r]
Luk et al. (2011)	Bland and Altman (mm [CI])	(0.0–0.1 [−0.8 to 0.8])[p], (0.0–0.1 [−0.7 to 0.8])[r]	1 examiner
Al-Ekrish & Ekram (2011)	Cronbach's alpha/% > with absolute difference larger than 0.5 mm	(0.997/10%)[r], (0.999/2%)[p]	(0.979/75%)[r]
Kamburoglu et al. (2009)	ICC/range in mm (aka repeatability)	(0.86 to 0.97/0.78 to 2.05)[r] (0.98 to 0.99/0.43 to 1.07)[p]	(0.84 to 0.97/0.76 to 1.99)[r] (0.78 to 0.97/1.22 to 2.59)[p]
Veyre-Goulet et al. (2008)	NR	—	—
Loubele et al. (2008)	2-way ANOVA (p value)	(0.996)[p]	(0.934)[p] (0.20)[r]
Kobayashi et al. (2004)	NR	—	—

ICC, Intraclass correlation coefficient; *SD*, standard deviation; NR, not reported; p, physical measurements; r, radiographic measurements; CI, 95% confidence interval.

whereas others provided no statistical information (Kobayashi et al., 2004; Sheikhi et al., 2015; Waltrick et al., 2013).

The results of several authors show a high correlation between CBCT and the gold standard using different correlation parameters (Alkan et al., 2016; Luangchana et al., 2015; Neves et al., 2014; Waltrick et al., 2013). However, one author showed only moderate correlation (Eachempati et al., 2016). Kamburoglu et al. (2009) reported overall ICC values of 0.61 to 0.93 and 0.4 to 0.95 for two observers. The authors indicated that the low values (0.61 and 0.4) were only for measurements of the distance between the mandibular canal and the surface of the lingual cortical plate. Sheikhi et al. (2015) also reported high ICC values for height (0.89) and width (0.91). Eachempati et al. (2016) also reported high level of agreement among the clinical gold standard, ridge mapping, and CBCT measurements, with 94.6% of the data being within the mean and one standard deviation in a Bland–Altman plot.

No clear trend in measurement error is apparent as authors report both overestimation (Al-Ekrish, 2012; Al-Ekrish & Ekram, 2011; Al-Ekrish et al., 2013; Freire-Maia et al., 2017; Gerlach et al., 2013, 2014; Kobayashi et al., 2004; Loubele et al., 2008; Luk et al., 2011; Pena de Andrade et al., 2016; Vasconcelos et al., 2015; Waltrick et al., 2013) and underestimation (Alkan et al., 2016; Eachempati et al., 2016; Freire-Maia et al., 2017; Ganguly et al., 2016; Luangchana et al., 2015; Pena de Andrade et al., 2016; Santana et al., 2012; Sheikhi et al., 2015; Torres et al., 2012; Vasconcelos et al., 2015; Veyre-Goulet et al., 2008; Waltrick et al., 2013) between CBCT and the "gold standard" measurements.

3.7 | Outcomes of assessment of reiliability (repeatability/reproducibility)

Inter- and intra-observer reliabilities were reported in most of the 22 studies included (Table 5). One study described performing interobserver analysis, but the results were not reported (Santana et al., 2012), and in three studies, data were only provided for one

TABLE 6 Quality assessment of the included clinical studies: blue = Luk et al. (2011); red = Eachempati et al. (2016)

Criteria	Yes	No	Other(CD,NR.NA)
1. Was the research question or objective in this paper clearly stated?	◆◆		
2. Was the study population clearly specified and defined?	◆◆		
3. Was the participation rate of eligible persons at least 50%?			NR NR
4. Were all the subjects selected or recruited from the same or similar populations (including the same time period)? Were inclusion and exclusion criteria for being in the study prespecified and applied uniformly to all participants?	◆	◆	
5. Was a sample size justification, power description, or variance and effect estimates provided?	◆		CD
6. For the analyses in this paper, were the exposure(s) of interest measured prior to the outcome(s) being measured?		◆◆	
7. Was the timeframe sufficient so that one could reasonably expect to see an association between exposure and outcome if it existed?		◆◆	
8. For exposures that can vary in amount or level, did the study examine different levels of the exposure as related to the outcome (e.g., categories of exposure, or exposure measured as continuous variable)?			NA NA
9. Were the exposure measures (independent variables) clearly defined, valid, reliable, and implemented consistently across all study participants	◆		
10. Were the exposure measures (independent variables) clearly defined, valid, reliable, and implemented consistently across all study participants	◆		CD
11. Were the outcome measures (dependent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?	◆◆		
12. Were the outcome assessors blinded to the exposure status of participants?			NA NA
13. Was loss to follow-up after baseline 20% or less?			NA NA
14. Were key potential confounding variables measured and adjusted statistically for their impact on the relationship between exposure(s) and outcome(s)?	◆◆		

CD, cannot determine; NA, not applicable; NR, not reported.

observer (Luk et al., 2011; Torres et al., 2012; Vasconcelos et al., 2015). A variety of methods were used for to describe reliability including intraclass correlation coefficient alone or together with Cronbach's alpha, range in millimeters or Bland and Altman, Bland and Altman alone, the Pearson correlation coefficient alone or together with Cronbach's alpha or standard deviation, Cronbach's alpha alone or together with percentage of measurements with an absolute difference greater than 0.5 mm and respective *p*-value.

Values for all studies reporting inter- and intra-observer were high (Table 5).

3.8 | CBCT imaging parameters

There was no consistency in the reporting of exposure, acquisition or display protocols used among the included studies (Table 4). In addition, no author reported on the standardization of these parameters with respect to the gold standard. Some authors deliberately modified selected parameters and found no effects on measurement accuracy. This included voxel size (Ganguly et al., 2016; Luangchana et al., 2015; Torres et al., 2012; Waltrick et al., 2013), scan times (Al-Ekrish, 2012; Waltrick et al., 2013), software used for analysis (Vasconcelos et al., 2015), and display monitor (Al-Ekrish et al., 2013). Only one author investigated the use of two different CBCT units and found no difference in measurement accuracy (Luangchana et al., 2015). Torres et al. (2012) recommended a voxel size of 0.3 to 0.4 mm^3 as a good compromise between image quality and reduced radiation exposure.

3.9 | Comparison to other radiographic diagnostic methods

CBCT measurement accuracy was compared most often to MSCT with five ex vivo studies (Al-Ekrish & Ekram, 2011; Freire-Maia et al., 2017; Kobayashi et al., 2004; Loubele et al., 2008; Pena de Andrade et al., 2016) and panoramic radiography with three studies (Alkan et al., 2016; Eachempati et al., 2016; Luangchana et al., 2015). One study compared CBCT to digital radiography and digital photography (Alkan et al., 2016), and another compared it to tangential projection (Sheikhi et al., 2015).

Freire-Maia et al. (2017), Pena de Andrade et al. (2016) and Loubele et al. (2008) found no significant differences in accuracy between CBCT imaging and MSCT regarding the accuracy of linear measurements, and reported submillimeter error ranges for both radiographic techniques (Freire-Maia et al., 2017; Loubele et al., 2008; Pena de Andrade et al., 2016). However, Kobayashi et al. (2004) and Al-Ekrish et al. (2013) reported significant differences in measurement error between CBCT and MSCT (Al-Ekrish et al., 2013; Kobayashi et al., 2004), particularly for width measurements (Al-Ekrish et al., 2013), at mandibular sites (Al-Ekrish et al., 2013), and at specific regions (Al-Ekrish et al., 2013; Kobayashi et al., 2004).

Studies comparing measurement accuracy of CBCT and panoramic radiography are limited, and the results are equivocal. Alkan et al. (2016) demonstrated that CBCT and digital radiography measurements were significantly correlated to the gold standard, in contrast to panoramic imaging, where mesiodistal linear measurements differed significantly. Luangchana et al. (2015) reported no difference between CBCT and panoramic radiography in the mean measurement difference of vertical alveolar bone, but absolute and percentage differences were significantly less for CBCT than panoramic radiography, particularly in the mandible. These findings are supported by Eachempati and coworkers (Eachempati et al., 2016), who found a high correlation between height measurement in CBCT and panoramic radiography utilizing metallic ball markers as fiducial markers.

3.10 | Quality assessment of included studies

The majority of the included studies were ex vivo (20 of 22), and thus, a quality assessment for these studies was not performed. For the two remaining clinical studies, the NIH "Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies" was applied (Table 6). Domains on exposure and follow-up of this assessment tool do not apply for the current studies. Only one of the two studies reported a power description of the sample size.

4 | DISCUSSION

Successful dental implant treatment should incorporate a thorough planning phase using an appropriate radiographic examination providing images of diagnostic quality (Freire-Maia et al., 2017; Neves et al., 2014). Three-dimensional presurgical assessment is often necessary to identify vital anatomical structures (e.g., mandibular canal, maxillary sinus floor, mental foramen) and assessing the bone quantity and quality, which will maximize the potential for success of the inserted implants (Molly, 2006; Turkyilmaz & McGlumphy, 2008), and facilitate bone grafting procedures (Verdugo, Simonian, Smith McDonald & Nowzari, 2009). CBCT imaging is now commonplace and has become popular for diagnostic procedures, especially in implant dentistry. Compared to MSCT, CBCT provides cross-sectional and 3D imaging at reduced radiation exposure (Freire-Maia et al., 2017; Patel, 2009) at an overall lower price (Scarfe et al., 2006). The majority of clinicians consider CBCT images to be reliable and distortion free and are unaware of potential inaccuracies or inconsistencies that may exist when performing linear measurements or evaluating bone and anatomic structures prior to implant placement.

Many authors have reported bone measurements made on CBCT images can be considered accurate, when errors less than 1 mm can be tolerated (Kobayashi et al., 2004; Torres et al., 2012; Wyatt & Pharoah, 1998). Most studies in our review showed submillimeter accuracy of CBCT measurements compared to a gold standard. There was no clear trend as to whether measurements are consistently under- or overestimated. However, the range of absolute error in some studies exceeded the clinically considered threshold of 1 mm. This finding may be of clinical importance as it implies that the previously stated submillimeter accuracy of CBCT for preoperative evaluation of implant sites may, in some circumstances, be insufficient and could potentially lead to clinical complications. The higher radiographic contrast of radiopaque markers used in several of the included studies may contribute to increased accuracy of the ex vivo measurements. On the other hand, some have claimed that the embalming fluid associated with cadaver specimens might be partially responsible for reduced accuracy compared to measurements on patients. Several authors

have suggested a 2 mm safety zone for measurements obtained from panoramic radiography (Bartling, Freeman & Kraut, 1999; Buser & von Arx, 2000; Greenstein & Tarnow, 2006). Considering the inhomogeneity of data from our current review and the lack of conclusive evidence from clinical studies, we also recommend a safety margin of 2 mm from vital anatomical structures, when using 3D data from CBCT imaging.

It is possible that specific makes and models of CBCT equipment may have different levels of accuracy in linear measurements of the residual alveolar ridge. This could be potentially because of the many machine-specific, operator-independent variables such as filtration, target-object/object-sensor distances, reconstruction algorithms used, or different designs of head restraining devices that could potentially influence measurement accuracy. However, due to the inhomogeneity of the dependent variables identified (linear measurement indices) in this review, further attempts at identifying these machine-specific conditions for the purposes of comparison would not add to the outcomes of the present analysis as even the metric data from seemingly the same machine by two different investigators are not comparable.

In one study, the maxillary measurements were found to be less accurate than those of the mandible (Luangchana et al., 2015). This may be explained a potential reduction in overall density of the maxilla than the mandible due to the thinner cortical layer and greater cancellous component. On the other hand, Gerlach et al. (2013) found overestimation of mandibular dimensions on CBCT cross-sectional images, especially when assessing the cortical thickness (Gerlach et al., 2013). This finding may result from errors introduced when measuring short distances on CBCT images with limited spatial resolution acquired at relatively large voxel dimensions (Molen, 2010) or to partial volume averaging, which appears when different bone densities appear in the same voxel (Barrett & Keat, 2004; Molen, 2010).

As expected, the majority of studies were in vitro—either on dry skulls or on cadaver samples—with only two clinical studies identified. Clinical studies are inherently difficult to perform as they require accurate, physical measurements of the bone intraoperatively. Due to the nature of the ex vivo studies, a quality assessment of these investigations was not performed. Ex vivo studies are ranked low within the spectrum of strength of evidence within the hierarchical pyramid in a clinical setting (Hujoel, 2009). Nevertheless, the importance and validity of these studies should not be undervalued as they are observational diagnostic studies, where findings can be extrapolated to daily clinical practice. The outcome reports of the two cross-sectional clinical studies were analyzed and the overall risk of potential for bias was considered as limited.

In terms of sample size, the number of measurements for CBCT varied from 8 (Loubele et al., 2008) to 255 (Alkan et al., 2016). It appears that most authors arbitrarily determined sample size without performing power calculations. Without a power analysis, it is difficult to determine the external validity of the reported outcomes. Most authors reported that measurements were carried out by two or more observers, except for one study where the number of observers was unreported (Pena de Andrade et al., 2016) and two studies that had only one examiner (Luk et al., 2011; Santana et al., 2012). Although calibration of the examiners is necessary for optimal diagnostic performance and reliability (de Oliveira et al. 2009), only two authors reported that a measurement calibration procedure was performed, but without details (Eachempati et al., 2016; Vasconcelos et al., 2015). The reported inter- and intra-examiner agreement was very high for all the studies.

There was a large heterogeneity of devices, parameters and software used in the included studies, which made a direct comparison impossible. Several studies reported that smaller voxel sizes did not lead to greater accuracy for the linear measurements at edentulous sites (Ganguly et al., 2016; Luangchana et al., 2015; Torres et al., 2012; Waltrick et al., 2013). This is in agreement with other CBCT studies comparing different voxel sizes (Damstra, Fourie, Huddleston Slater & Ren, 2010; Liedke, da Silveira, da Silveira, Dutra & de Figueiredo, 2009; Patcas, Muller, Ullrich & Peltomaki, 2012). Voxel size plays a significant role in image quality as it defines the spatial resolution of the CBCT images (Patel, Dawood, Ford & Whaites, 2007; Scarfe et al., 2006; Watanabe, Honda, Tetsumura & Kurabayashi, 2011), providing higher degree of detail. High resolution has been reported to influence diagnostic tasks in other applications fields, like endodontics (Kamburoglu & Kursun, 2010; da Silveira et al., 2013), but for implant treatment planning, a voxel size of 0.3 to 0.4 mm seems to be sufficient to provide the necessary accuracy. Similarly, our review indicates that numerous radiation dose reduction settings such as limitation of field of view (Ganguly et al., 2016), reducing scan time (Al-Ekrish, 2012; Waltrick et al., 2013), or scan arc (Neves et al., 2014) can be applied without adversely affecting the accuracy of measurements on cross-sectional CBCT images.

There appear to be no differences between software packages in measuring CBCT images (Vasconcelos et al., 2015). Nevertheless, clinicians should be cautious when using new software as there is little scientific, evidence-based validation of the performance of these algorithms.

Clinical extrapolation of the findings from ex vivo CBCT studies is inherently problematic as CBCT reconstruction algorithms are optimized for in vivo scanning of maxillofacial areas, which are composed of both skeletal and soft tissue elements. In addition, high-density materials such as root canal fillings, composite resins, metallic restorations, and dental implants create beam hardening artifacts (Schulze, Berndt & d'Hoedt, 2010). Therefore, as most experimental conditions using dry skulls or formalin-fixed cadavers are not equivocal to clinical situations, the accuracy of linear measurements obtained ex vivo may not be directly comparable to in vivo situations and may result in over- or underestimation. Soft tissues attenuate the X-ray beam, reducing tissue contrast increasing scatter and contributing to image noise, thus potentially affecting the accuracy of the relative measurements (Ganguly et al., 2016; Gerlach et al., 2013; Patcas et al., 2012). Recent studies though have shown that accuracy outcomes were similar with and without soft tissues (Ganguly et al., 2011; Wood et al., 2013). Wood et al. (2013) showed that the presence of soft tissues had

no effect when a 0.4 mm voxel size was used, and 0.2-mm scans demonstrated a clearly inferior accuracy associated with absence of soft tissues. Even though not directly comparable, all studies in the current review reported high accuracy outcomes for the linear measurements, irrespective of the presence or absence of soft tissues or soft tissue simulation, supporting the assertion that the presence of soft tissues in ex vivo CBCT studies is not a crucial factor for accuracy measurements.

Digital calipers were used in the majority of studies to provide gold standard dimensions on histologic sections to which linear measurements on CBCT images were compared. While an accuracy of 0.01 mm or 0.02 mm accuracy was commonly reported, calipers were tested and calibrated only in three studies (Al-Ekrish, 2012; Al-Ekrish & Ekram, 2011; Al-Ekrish et al., 2013). While the precision with which a repeated point of insertion of the caliper on the sectioned specimens is arguable, the high inter- and intra-observer agreement reported on most studies support the validity of this method. Gerlach et al. performed measurements on digitized histological sections with great accuracy as confirmed by the small standard deviations (Gerlach et al., 2013, 2014). These authors attributed this finding to the use of methyl methacrylate as an embedding medium for the sections, which prevents shrinking artifacts (Wittenburg, Volkel, Mai & Lauer, 2009; Yang, Davies, Archer & Richards, 2003).

The two clinical studies included used ridge mapping for assessing the width of the edentulous alveolar ridge. Although it was not explicitly mentioned in these studies that this method is used as a control for the linear CBCT measurements, it was decided to include them in the present review as they fitted the presented inclusion and exclusion criteria. Despite the high agreement of the reported measurements in these studies, one should acknowledge certain limitations of this method such as the ability to accurately stop the measuring instruments at the first bone contact after penetrating the soft tissues, especially when the mucosa is mobile or the bone density is low, as well as to reproduce the point of entry precisely with the templates used for this purpose.

Finally, it must be mentioned that the current systematic review focused only on the accuracy of linear bone measurements on cross-sectional and therefore multiplanar reformatted, two-dimensional CBCT images. However, CBCT imaging provides three-dimensional depiction of bony structures, making it a crucial diagnostic tool that, in addition to linear measurements, enables evaluation of the morphology, bone quality, and volume of the residual alveolar ridge, which are also important and basic considerations in overall implant site assessment.

5 | CONCLUSIONS

Based on the results of this systematic review, it can be concluded that:

- CBCT provides cross-sectional images that demonstrate high accuracy and reliability for bony linear measurements on cross-sectional images related to implant treatment. Therefore, CBCT is an appropriate diagnostic tool for 3D preoperative planning.
- A wide range of error has been reported when performing linear measurements on CBCT images, with both over- and underestimation of dimensions in comparison with a gold standard. Therefore, a 2 mm safety margin to adjacent anatomic structures should be considered when using CBCT.
- A voxel size of 0.3 to 0.4 mm is adequate to provide CBCT images of acceptable diagnostic quality for implant treatment planning.
- As most studies were ex vivo (i.e., dry skulls or cadavers), the reported results should be considered optimal. In clinical practice, measurement accuracy and reliability are most likely reduced as several factors (e.g., patient motion, device and software used, manual or automated procedures) might influence linear measurements on CBCT images.
- Due to the inhomogeneity of the extracted data from the included studies, it was not possible to conduct a meta-analysis to account for multivariate effect estimates. Thus, further studies that focus on determining which factors specifically influence the accuracy of the measurements in 3D imaging are recommended.

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SUPPORTING INFORMATION

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How to cite this article: Fokas G, Vaughn VM, Scarfe WC, Bornstein MM. Accuracy of linear measurements on CBCT images related to presurgical implant treatment planning: A systematic review. *Clin Oral Impl Res*. 2018;29(Suppl. 16):393–415. https://doi.org/10.1111/clr.13142