RESEARCH ARTICLE

Dimensional accuracy of cone beam CT with varying angulation of the jaw to the X-ray beam

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Objectives: Cone beam CT (CBCT) machines do not always allow for patients to be scanned in the ideal position for image acquisition. This study aimed to investigate the influence of the position/angulation of the mandible relative to the X-ray beam of a CBCT machine.

Methods: Five sequential CBCT scans were captured of a human mandible at each angulation of 10°, 20°, 30°, and 40° using a coronal and sagittal positioning. Inspection software utilized a best-fit alignment to automatically calculate the three-dimensional variation at 15 standardized points of interest.

Results: Statistically significant differences were found between the dimensional accuracy of CBCT scans taken at 10° (26.3 µm) of coronal angulation, as well as those taken at 20° (−17.3 mm) and 30° (35.2 mm) of sagittal angulations ($p < 0.001$, 0.016, and <0.001 , respectively). The largest deviations in accuracy included an overall maximum deviation of 490 µm.

Conclusions: The position of the mandible with respect to the X-ray beam has a clinically insignificant effect on dimensional accuracy, up to the maximum angle of 40° assessed.

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Introduction

The 1990s saw the adoption of digital three-dimensional (3D) diagnostics into dentistry,^{1,2} with CT being adopted from the medical realm into the dental setting.³ In the early 2000s this was followed by the development of cone beam CT (CBCT) which has gained widespread use in dentistry.⁴ The impetus for the development and expansion of CBCT in dentistry was its diagnostic application for dental implant planning.^{1,5} Current digital protocols in implant dentistry depend on the accurate integration of 3D diagnostic information from radiographs (CBCT), digital intraoral impressions and

prosthetic designs which can be used for virtual implant planning.⁶ The integration of these modalities also allows for the use of guided implant surgery which can help minimize surgical morbidity and risks for patients.⁷

CBCT has some disadvantages compared to medical multislice CT, including poorer image quality related to noise and poorer contrast resolution resulting from the presence of large amounts of scattered radiation.⁸ Nevertheless, CBCT has displaced medical CT in much of dentistry because it is more affordable, exposes patients to less radiation, and the machines are more compact, allowing for in-house use in a dental office.⁹ CBCT machines do not always allow for patients to be scanned in the ideal position for image acquisition. For example, obese patients or patients with medical

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Figure 1 Human mandible on radiolucent foam in CBCT machine.

conditions such as torticollis can be challenging to position correctly within the X-ray field.¹⁰

It has previously been shown using medical CT that an accurate plane of acquisition is essential to obtaining accurate measurements.^{11–13} By comparison, there is a dearth of information concerning how patient positioning affects the accuracy of measurements on CBCT scans which are currently the preferred dento-maxillofacial 3D imaging modality. Previous studies concerning the accuracy of measurements performed on CBCT scan have included limitations that may include a significant degree of human error. For example, some investigators used a gauge to compare physical landmarks on a skull to the landmarks on CT,^{14–16} while others performed 3D superimposition using manual^{17,18} or semi-automatic alignment.^{19–25}

The purpose of this *in-vitro* study was to determine the influence of the position of the mandible relative to the X-ray beam of a CBCT machine on the accuracy of measurements performed on the CBCT image, utilizing a protocol that excluded human error to the greatest extent reasonably possible. Our null hypothesis was that no significant difference exists in the dimensional accuracy of CBCT scans captured at varied angulations.

Methods and materials

One dry human mandible with four teeth (#s19, 21, 28, 30) and no dental restorations was used for the radiographic evaluation. (Figure 1) Three radiographic markers (CT-Spot®, Beekley Medical, Bristol CT) were applied to the mandible at the sites of the mental protuberance and the right and left angle, respectively. These sites were chosen for their smooth anatomical morphology allowing the radiographic markers to adhere reliably. A custom-fabricated stand that fit in the CBCT unit while still allowing the machine to rotate freely was manufactured. The mandible was mounted to ensure that at zero degrees, the occlusal plane of the mandible was parallel to the horizontal plane. The mandibular occlusal plane was used as the reference plane and the zero degrees angle was parallel to the horizontal plane and used as the control. Wooden wedges with 10°, 20°, 30°, and 40° were utilized to support the mandible within the CBCT machine at the specified angulations with respect to the X-ray beam. A radiolucent foam pad was placed between the mandible and the wooden supporting wedge to minimize any radiographic noise. A measuring device was used to ensure that the target to object distance remained constant.

Scans were exposed with the I-CAT Next Generation CBCT unit (Imaging Sciences International, Hatfield, PA). Prior to exposing the images, physical calibration of the X-ray unit and flat panel X-ray sensor were carried out according to the manufacturer's directions. The exposure factors utilized were: kVp = 120, mA = 5, mAs = 18.54, 8.9 s, and 0.4 voxel. The voxel size chosen was in accord with the normal clinical protocol for diagnostic implant CBCT at our institution, in keeping with the principle of as low as diagnostically acceptable.²⁶

A CBCT scan taken with the mandible parallel to the floor was utilized as the control dataset. (Figure 2) Five sequential CBCT scans were captured at each angulation of 10°, 20°, 30°, and 40° to simulate an anterior or coronal tilt of the jaw. Five sequential CBCT scans were also captured at each of the 10°, 20°, 30°, and 40°

Figure 2 Illustration of Mandible mounted at 0–40 degrees. Radiographs were captured in both the coronal and sagittal orientations.

Figure 3 Geomagic screenshot depicting dimensional differences between scans (mm).

angulations with the support turned 90 degrees to simulate a left-to-right (sagittal) tilt.

Each of the Digital Imaging and Communications datasets obtained from the CBCT scans was converted to surface renderings (3D Slicer 4.5.0, www.slicer.org) and exported in Standard Tessellation Language file format.

(Figure 3) Dimensional differences between the various datasets were measured with an inspection software application (Geomagic Qualify 12.0; 3D systems, Andover, MN). A computer-generated best-fit algorithm utilized all data points in each Standard Tessellation Language dataset to align all scans into the same 3D coordinate system as the control reference dataset. After being aligned into the same 3D coordinate system as the control reference dataset, the dimensional deviations were calculated at 15 standardized points. These included the three CT-Spot radiographic markers, the buccal and lingual cusp tips of the left and right first premolars, and the mesiobuccal, mesiolingual, distobuccal, and distolingual cusp tips of the left and right first molars. Utilizing this method, the same standardized points could be measured in a repeatable manner. The dimensional deviations were calculated based on their divergence in the x -, y -, z - axes. Positive or negative values indicate that the test dataset is superior or inferior to the reference control dataset. The average dimensional deviation was calculated from the 15 data points in each scan.

The reference control dataset was re-oriented digitally within the inspection software and then aligned with the original to determine the software error of alignment. Dimensional variation between the five datasets taken at the same angulation was utilized to assess the precision of the CBCT scans. Dimensional variation between the reference control dataset and each of the test datasets was utilized to determine the accuracy of the CBCT scans at each of the angulations tested.

The 15 standardized points were pooled by individual teeth and radiographic markers to represent seven measurement areas. A descriptive analysis was conducted for the average deviations in the x , y , and z axes. In order to compare the accuracy of the CBCT scans taken at the various angulations, we performed the linear mixed effects regression²⁷ using the lme4 package²⁸ in the statistical software R (v. 3.4.3, R Core Team). The model allows one to account for the correlations between the repeated measurements. Statistical inference for the accuracy of the CBCT scans was made through the fixed effects of angulation-specific indicator variables and false discovery rate was controlled at 5%, accounting for multiple comparisons.²⁹ The adequacy of the regression model was assessed via the visual inspection of the plot of the standardized residuals and fitted values. In order to compare the precision of the CBCT scans at the various angulations, we used a non-parametric multivariate analysis of variance test³⁰ to determine whether there is a statistically significant difference in dimensional deviations among the five scans.

Results

The software alignment algorithm was found to contribute 0.000 mm of error. Average dimensional deviations and standard deviations from the seven measurement areas between each of the five scans taken at the same angulation, representing the variation in precision of the angulated CBCT scans, are displayed in Table 1. The largest deviations between the scans within each group included a range from 0.118 to -0.291 mm and an overall maximum deviation of 0.409 mm. Overall average variations within the groups ranged from 0.011 mm (± 0.024) to 0.023 mm (± 0.036).

Table 1 Intragroup Variation. Mean dimensional deviations and standard deviations (mm) by test group

Group/landmark	Coronal angulation				Sagittal angulation			
	10°	20°	30°	40°	10°	20°	30°	40°
All points	0.012 (±0.027)	0.016 (±0.034)	0.011 (±0.031)	0.021 (±0.025)	0.011 (±0.024)	0.014 (±0.036)	0.015 (±0.024)	0.023 (±0.036)
Largest ± variation	0.099/−0.052	0.118/−0.061	0.078/−0.113	0.086/−0.034	0.063/−0.042	0.105/−0.090	0.081/−0.043	0.095/−0.077
Anterior marker	−0.026 (±0.010)	−0.014 (±0.016)	−0.010 (±0.007)	−0.001 (±0.007)	0.016 (±0.015)	−0.002 (±0.022)	0.008 (±0.010)	−0.011 (±0.011)
Right posterior marker	0.024 (±0.024)	−0.013 (±0.012)	−0.002 (±0.004)	0.000 (±0.014)	−0.007 (±0.012)	−0.004 (±0.017)	0.011 (±0.008)	−0.010 (±0.013)
Left posterior marker	−0.017 (±0.018)	0.006 (±0.014)	0.001 (±0.014)	−0.003 (±0.010)	0.001 (±0.003)	−0.006 (±0.010)	−0.003 (±0.003)	−0.001 (±0.009)
#19	0.012 (±0.022)	0.008 (±0.023)	0.013 (±0.022)	0.022 (±0.021)	0.011 (±0.017)	0.015 (±0.048)	0.014 (±0.019)	0.022 (±0.021)
#21	0.031 (±0.028)	0.011 (±0.003)	0.020 (±0.042)	0.031 (±0.022)	0.024 (±0.017)	0.009 (±0.028)	0.026 (±0.031)	0.031 (±0.022)
#28	0.007 (±0.015)	0.032 (±0.019)	−0.010 (±0.018)	0.019 (±0.030)	−0.013 (±0.031)	0.036 (±0.041)	0.006 (±0.019)	0.019 (±0.030)
#30	0.007 (±0.009)	0.065 (±0.036)	0.033 (±0.031)	0.036 (±0.024)	0.021 (±0.024)	0.028 (±0.020)	0.017 (±0.024)	0.036 (±0.024)

Average dimensional deviations and standard deviations from the seven measurement areas between each of the tested angulations and the reference control dataset, representing the variation in accuracy of the angulated CBCT scans, is displayed in [Table 2](#). The largest deviations in accuracy between the test scans and the control scan included a range from 0.137 to −0.353 mm and an overall maximum deviation of 0.490 mm. Overall average variations between the control and angulated groups ranged from −0.017 mm (±0.066) to 0.035 mm (±0.039). The three radiographic markers had greater precision when compared to standardized points on the natural dentition.

Statistically significant differences were found between the dimensional accuracy of CBCT scans taken at 10° (0.0263 mm) of coronal angulation, as well as those taken at 20° (−0.0173 mm) and 30° (0.0352 mm) of sagittal angulations ($p < 0.001$, 0.016, and <0.001, respectively, in [Table 3](#)). A non-parametric analysis of variance test ($P 0.97$) showed no statistically significant differences for the precision of CBCT scans taken at various angulations.

Discussion

Whilst most patients are able to be positioned reasonably optimally for acquisition of a CBCT image, occasionally patients cannot be placed in the ideal position. This gives rise to the question of whether head positioning/angulation would affect the dimensional accuracy and reliability of the CBCT scan for pre-operative virtual implant planning.

The accuracy of CBCT is of importance to clinicians in the diagnosis and pre-operative planning for implant surgery. Previous studies have investigated landmarks on radiological images and compared them to physical landmarks using a gauge.^{14–16} The disadvantage of these studies is that by using a measuring gauge they incorporate human error in performing measurements. Human error resulted in standard deviations of 0.2 mm up to 1.4 mm.¹⁷

To eliminate human error, Von Wilmsky et al and Matta et al used 3D superimposition as a method to evaluate the accuracy of CBCT.^{17,18} In both instances the master scan was captured optically using a non-contact white-light scanner. The master scan was then compared to CBCT test scans following a best-fit alignment. The shortcoming of this method is that one must manually select the specific areas for the best-fit software function. Also, 3D superimposition is limited based upon the surface detail of both scans. In effect, the superimposition process is contributing error to the analysis. Both studies described a standard deviation of between 0.0593 to 0.072mm. In addition to non-contact white-light scanner, micro CT is another example of a gold standard used for accuracy of CBCT studies.

Table 2 Test group variation. Mean dimensional deviations and standard deviations (mm) by test group

Group/landmark	Coronal angulation				Sagittal angulation			
	0° vs 10°	0° vs 20°	0° vs 30°	0° vs 40°	0° vs 10°	0° vs 20°	0° vs 30°	0° vs 40°
All points	0.026 (±0.040)	-0.004 (±0.044)	0.016 (±0.039)	-0.003 (±0.048)	-0.013 (±0.041)	-0.017 (±0.066)	0.035 (±0.039)	-0.009 (±0.047)
Largest ± variation	0.114/-0.163	0.105/-0.135	0.130/-0.074	0.007/-0.128	0.049/-0.174	0.079/-0.353	0.136/-0.057	0.092/-0.122
Anterior marker	0.032 (±0.015)	0.000 (±0.015)	-0.015 (±0.012)	-0.034 (±0.006)	0.016 (±0.006)	0.011 (±0.021)	-0.042 (±0.013)	-0.044 (±0.013)
Right posterior marker	0.057 (±0.022)	0.045 (±0.011)	0.044 (±0.004)	0.027 (±0.013)	0.020 (±0.012)	0.015 (±0.012)	0.047 (±0.010)	0.003 (±0.014)
Left posterior marker	0.021 (±0.021)	-0.008 (±0.013)	-0.019 (±0.011)	-0.068 (±0.011)	-0.042 (±0.005)	-0.069 (±0.014)	0.010 (±0.010)	-0.067 (±0.005)
#19	0.016 (±0.048)	-0.027 (±0.037)	-0.007 (±0.040)	-0.027 (±0.038)	-0.023 (±0.038)	-0.059 (±0.087)	0.034 (±0.037)	-0.015 (±0.039)
#21	0.021 (±0.046)	-0.029 (±0.048)	0.023 (±0.028)	0.016 (±0.033)	-0.003 (±0.034)	-0.009 (±0.017)	0.060 (±0.037)	-0.034 (±0.039)
#28	0.050 (±0.011)	0.039 (±0.026)	0.064 (±0.035)	0.060 (±0.046)	-0.003 (±0.059)	0.008 (±0.060)	0.029 (±0.025)	0.020 (±0.044)
#30	0.019 (±0.036)	-0.004 (±0.045)	0.019 (±0.025)	-0.004 (±0.034)	-0.036 (±0.041)	0.005 (±0.053)	0.038 (±0.017)	0.014 (±0.048)

Al-rawi et al compared CBCT to micro CT with a voxel setting of 0.250 mm.²² The scans were segmented in a semi-automatic manner before being compared to micro CT. The mean and maximum differences between CBCT and micro CT was 207 ± 80 (max 862) μm respectively. By comparison, we used a voxel setting of 0.400 mm which yielded an overall maximum deviation of 0.490 mm. Overall average variations between the control and angulated groups ranged from -0.017 mm (± 0.066) to 0.035 mm (± 0.039). Our study utilized a CBCT scan as both the control and the test dataset. Software alignment utilized all points in all scans and did not require manual selection of similar surfaces. The software alignment was found to contribute 0.000 mm error.

In our study, statistically significant differences were found to exist between radiographs acquired with several of the coronal and sagittal angulations. This indicates that the position of the patient within the CBCT machine can have an impact on dimensional accuracy. This is in contrast to previous studies that have generally found no statistically significant difference. For example, Berco et al compared the relationship between the changes in rotation of skull and the linear measurements of CBCT. Linear measurements were made by human reviewers identifying anatomical landmarks. Their results show that no significant differences exist between linear measurements at varied orientations.³¹ Several other studies have confirmed this result using independent human reviewers to identify anatomical landmarks.³²⁻³⁴

Al-Rawi et al found that segmentation is the most important determinant for accuracy of CBCT 3D models.²² They suggested using global and local thresholding, image gradient, and active contour fitting to segment 3D models. Segmentation is labor intensive and time consuming. With manual segmentation, the validity of and accuracy of those techniques should be assessed against a gold standard. It should be noted that even a reliable gold standard such as microCT is affected by artifacts similar to those used in CBCT. Our study did not use any manual segmentation and no gold standard was used. This was only possible because we used a single, dry human mandible with no metal (e.g. restorations) for the study.

The importance of our study is in the methodology that underlies the manner in which the measurements were made. Our standardized points were identified only once, namely in the control CBCT dataset made with the occlusal plane of the mandible level in the CBCT machine. All measurements were performed by the inspection software for all subsequent scans at the same pre-determined location. Therefore, there is no intraoperator, inter operator, or other methodological error. Although the variation was found to be statistically significant, for clinical practice the differences are very small. It is likely that the differences detected in this study are due to the higher accuracy and less

Table 3 Statistical analysis

		Mean DEV (mm) (95% CI)	BH	p-value (<BH)
Coronal angulation	0° vs 10°	0.0263 (0.0123, 0.0404)	0.012	<0.001
	0° vs 20°	−0.0043 (−0.0183, 0.0097)	0.044	0.548
	0° vs 30°	0.0159 (0.0018, 0.0299)	0.025	0.027
	0° vs 40°	−0.0033 (0.0173, 0.0108)	0.050	0.648
Sagittal angulation	0° vs 10°	−0.0126 (−0.0267, 0.0014)	0.031	0.078
	0° vs 20°	−0.0173 (−0.0314, −0.0033)	0.019	0.016
	0° vs 30°	0.0352 (0.0211, 0.0492)	0.006	<0.001
	0° vs 40°	−0.0094 (−0.0234, 0.0046)	0.038	0.189

CI, confidence interval.

The average dimensional deviation.

The adjusted significance threshold from the Benjamini-Hochberg procedure.

error in the methodology which enabled the detection of such small variations.

Although the use of a single mandible may be perceived as a study limitation, the authors feel that it was beneficial in that it eliminated the operator error in selecting reference points. Selection of standardized points once was only possible because a single mandible was used in this study. If additional mandibles were to be used, the points would have to be selected in each mandible. Some might consider the use of a dry mandible without soft tissue and the absence of metal to be a limitation of our study. However, given the aim of our study, namely, to determine whether varied angulations of the mandible with respect to the beam of the CT unit affects the accuracy of measurements, it was important to eliminate as far as possible factors other than the angulation that may introduce artifacts and thus affect the accuracy of the measurements. The absence of soft tissue and metal allowed us to superimpose scans without needing any manual or semi-automatic segmentation. A water bath could have been used to simulate soft tissue, but, would have made precise positioning of the mandible extremely difficult and perhaps impossible.²⁴

Another limitation is that only one CBCT unit was used with specific parameters such as kVp, mA voxel size. It is possible that different exposure parameters and/or different CBCT systems may produce different results. Different conversion software may produce different reconstructions.

Because the resolution of the scans was set at 0.400 mm voxel size, our minimal difference of clinical significance may be set at 0.400 mm.³⁵ The maximum variation for intragroup scans was 0.409 mm. This can be contrasted with the maximum variation between the angulated groups and the control group of 0.490 mm. In the absence of any change in angulation, movement, or other confounding factors, sequential scans can be depended upon for their reliability within 0.409 mm. Changing angulation between scans resulted in a variation of up to 0.490 mm. The overall average dimensional deviation was very low, ranging from −0.017 mm (±0.066) to 0.035 mm (±0.039),

indicating a high degree of accuracy. It is unlikely that this variation would compromise the safety or efficacy of virtual implant planning or guided implant surgery if this variation is known and accounted for during the pre-surgical diagnostic planning. However, it is also recognized that error accumulates throughout the digital pathway and may become compounded along the chain of the virtual workflow.²⁵

The fact that the three radiographic markers had greater precision when compared to standardized points on the teeth was an incidental finding. The relatively inexpensive cost of the markers and the little time they take to place on and to remove from any appliance makes for a strong argument for always using radiographic markers even when the use of anatomical points appears to be reasonable. When comparing the intragroup and inter group mean volumetric deviations, the absolute value of the mean volumetric deviation was less for inter group at all points. This may indicate that CBCT is more precise when angulation/positioning is not altered between scans.

Conclusion

Within the limitations of the study the position of the mandible with respect to the X-ray beam has a clinically insignificant effect on dimensional accuracy, up to the maximum angle of 40° assessed. Increasing the angulation of the mandible, in both coronal and sagittal orientations, did not cause any clinically significant change to dimensional accuracy or precision of the CBCT scans. Whether a combination of a coronal and sagittal tilt would similarly have no effect remains to be studied. Radiographic markers can assist in providing accuracy in digital implant workflows. Further research into the clinical effects of errors propagation from the CBCT dataset into virtual implant planning and guided implant surgery is required.

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References

- Guerrero ME, Jacobs R, Loubele M, Schutyser F, Suetens P, van Steenberghe D. State-of-the-art on cone beam CT imaging for preoperative planning of implant placement. *Clin Oral Investig* 2006; **10**: 1–7. doi: <https://doi.org/10.1007/s00784-005-0031-2>
- Jacobs R, Quirynen M. Dental cone beam computed tomography: justification for use in planning oral implant placement. *Periodontol* 2000 2014; **66**: 203–13. doi: <https://doi.org/10.1111/prd.12051>
- Andersson J-E, Svartz K. CT-scanning in the preoperative planning of osseointegrated implants in the maxilla. *Int J Oral Maxillofac Surg* 1988; **17**: 33–5. doi: [https://doi.org/10.1016/S0901-5027\(88\)80226-1](https://doi.org/10.1016/S0901-5027(88)80226-1)
- Arai Y, Tammsalo E, Iwai K, Hashimoto K, Shinoda K. Development of a compact computed tomographic apparatus for dental use. *Dentomaxillofac Radiol* 1999; **28**: 245–8. doi: <https://doi.org/10.1038/sj.dmf.4600448>
- Bornstein MM, Horner K, Jacobs R. Use of cone beam computed tomography in implant dentistry: current concepts, indications and limitations for clinical practice and research. *Periodontol* 2000 2017; **73**: 51–72. doi: <https://doi.org/10.1111/prd.12161>
- Stapleton BM, Lin WS, Ntounis A, Harris BT, Morton D. Application of digital diagnostic impression, virtual planning, and computer-guided implant surgery for a CAD/CAM-fabricated, implant-supported fixed dental prosthesis: a clinical report. *J Prosthet Dent* 2014; **112**: 402–8. doi: <https://doi.org/10.1016/j.prosdent.2014.03.019>
- Tahmaseb A, Wismeijer D, Coucke W, Derksen W. Computer technology applications in surgical implant dentistry: a systematic review. *Int J Oral Maxillofac Implants* 2014; (29 Suppl): 25–42. doi: <https://doi.org/10.11607/jomi.2014suppl.g1.2>
- Scarfe WC, Farman AG. What is cone-beam CT and how does it work? *Dent Clin North Am* 2008; **52**: 707–30. doi: <https://doi.org/10.1016/j.cden.2008.05.005>
- Holberg C, Steinhäuser S, Geis P, Rudzki-Janson I. Cone-beam computed tomography in orthodontics: benefits and limitations. *J Orofac Orthop* 2005; **66**: 434–44. doi: <https://doi.org/10.1007/s00056-005-0519-z>
- Fursevich DM, LiMarzi GM, O'Dell MC, Hernandez MA, Sensakovic WF. Bariatric CT imaging: challenges and solutions. *Radiographics* 2016; **36**: 1076–86. doi: <https://doi.org/10.1148/rg.2016150198>
- Kim KD, Jeong HG, Choi SH, Hwang EH, Park CS. Effect of mandibular positioning on preimplant site measurement of the mandible in reformatted CT. *Int J Periodontics Restorative Dent* 2003; **23**: 177–83.
- Kohavi D, Bar-Ziv J, Marmar Y. Effect of axial plane deviation on cross-sectional height in reformatted computed tomography of the mandible. *Dentomaxillofac Radiol* 1997; **26**: 189–91. doi: <https://doi.org/10.1038/sj.dmf.4600242>
- Sforza NM, Franchini F, Lamma A, Botticelli S, Ghigi G. Accuracy of computerized tomography for the evaluation of mandibular sites prior to implant placement. *Int J Periodontics Restorative Dent* 2007; **27**: 589–95.
- Al-Ekrish AA. Effect of exposure time on the accuracy and reliability of cone beam computed tomography in the assessment of dental implant site dimensions in dry skulls. *The Saudi Dental Journal* 2012; **24**(3–4): 127–34. doi: <https://doi.org/10.1016/j.sdentj.2012.05.001>
- Medelink J, Hertrich K, Steinhäuser-Andresen S, Hirschfelder U, Hofmann E. Accuracy of anatomical landmark identification using different CBCT- and MSCT-based 3D images: an in vitro study. *J Orofac Orthop* 2011; **72**: 261–78. doi: <https://doi.org/10.1007/s00056-011-0032-5>
- Ganguly R, Ruprecht A, Vincent S, Hellstein J, Timmons S, Qian F. Accuracy of linear measurement in the Galileos cone beam computed tomography under simulated clinical conditions. *Dentomaxillofac Radiol* 2011; **40**: 299–305. doi: <https://doi.org/10.1259/dmfr/72117593>
- von Wilmsky C, Bergauer B, Nkenke E, Neukam FW, Neuhuber W, Lell M, et al. A new, highly precise measurement technology for the in vitro evaluation of the accuracy of digital imaging data. *J Craniomaxillofac Surg* 2015; **43**: 1335–9. doi: <https://doi.org/10.1016/j.jcms.2015.06.021>
- Matta RE, von Wilmsky C, Neuhuber W, Lell M, Neukam FW, Adler W, et al. The impact of different cone beam computed tomography and multi-slice computed tomography scan parameters on virtual three-dimensional model accuracy using a highly precise ex vivo evaluation method. *J Craniomaxillofac Surg* 2016; **44**: 632–6. doi: <https://doi.org/10.1016/j.jcms.2016.02.005>
- Ender A, Mehl A. Accuracy of complete-arch dental impressions: A new method of measuring trueness and precision. *J Prosthet Dent* 2013; **109**: 121–8. doi: [https://doi.org/10.1016/S0022-3913\(13\)60028-1](https://doi.org/10.1016/S0022-3913(13)60028-1)
- Lee SJ, Betensky RA, Gianneschi GE, Gallucci GO. Accuracy of digital versus conventional implant impressions. *Clin Oral Implants Res* 2015; **26**: 715–9. doi: <https://doi.org/10.1111/clr.12375>
- Steinhäuser-Andresen S, Detterbeck A, Funk C, Krumm M, Kasperl S, Holst A, et al. Pilot study on accuracy and dimensional stability of impression materials using industrial CT technology. *J Orofac Orthop* 2011; **72**: 111–24. doi: <https://doi.org/10.1007/s00056-011-0015-6>
- Al-Rawi B, Hassan B, Vandenberghe B, Jacobs R. Accuracy assessment of three-dimensional surface reconstructions of teeth from Cone Beam Computed Tomography scans. *J Oral Rehabil* 2010; **37**: 352–8. doi: <https://doi.org/10.1111/j.1365-2842.2010.02065.x>
- Sang YH, Hu HC, Lu SH, Wu YW, Li WR, Tang ZH, , S-H L, Y-W W, Li W-R TZ-H. Accuracy Assessment of Three-dimensional Surface Reconstructions of In vivo Teeth from Cone-beam Computed Tomography. *Chin Med J* 2016; **129**: 1464–70. doi: <https://doi.org/10.4103/0366-6999.183430>
- Hekmatian E, Jafari-Pozve N, Khorrami L. The effect of voxel size on the measurement of mandibular thickness in cone-beam computed tomography. *Dent Res J* 2014; **11**: 544–8.
- Koch GK, Gallucci GO, Lee SJ. Accuracy in the digital workflow: from data acquisition to the digitally milled cast. *J Prosthet Dent* 2016; **115**: 749–54. doi: <https://doi.org/10.1016/j.prosdent.2015.12.004>
- Ludlow JB, Timothy R, Walker C, Hunter R, Benavides E, Samuelson DB, et al. Effective dose of dental CBCT—a meta analysis of published data and additional data for nine CBCT units. *Dentomaxillofac Radiol* 2015; **44**: 20140197. doi: <https://doi.org/10.1259/dmfr.20140197>
- Laird NM, Ware JH. Random-effects models for longitudinal data. *Biometrics* 1982; **38**: 963–74. doi: <https://doi.org/10.2307/2529876>
- Bates D, Mächler M, Bolker B, Walker S. Fitting linear mixed-effects models using lme4. 2015; **2015**: 48.
- Benjamini Y, Hochberg Y. Controlling the false discovery rate: a practical and powerful approach to multiple testing. *J Royal Stat Soc Ser B* 1995; **57**: 289–300.
- Anderson MJ. A new method for non-parametric multivariate analysis of variance. *Austral Ecology* 2001; **26**: 32–46.
- Berco M, Rigali PH, Miner RM, DeLuca S, Anderson NK, Will LA. Accuracy and reliability of linear cephalometric measurements from cone-beam computed tomography scans of a dry human skull. *Am J*

- Orthod Dentofacial Orthop* 2009; **136**: e19: 17.e1: 17.e9. doi: <https://doi.org/10.1016/j.ajodo.2008.08.021>
32. Ludlow JB, Gubler M, Cevidanes L, Mol A. Precision of cephalometric landmark identification: cone-beam computed tomography vs conventional cephalometric views. *Am J Orthod Dentofacial Orthop* 2009; **136**: 312.e1–312.e10. doi: <https://doi.org/10.1016/j.ajodo.2008.12.018>
33. Shahidi S, Feiz A. Effect of Minor Amendments of Patient's Position on the Accuracy of Linear Measurements Yielded from Cone Beam Computed Tomography. *J Dent* 2013; **14**: 1–5.
34. Hassan B, van der Stelt P, Sanderink G. Accuracy of three-dimensional measurements obtained from cone beam computed tomography surface-rendered images for cephalometric analysis: influence of patient scanning position. *Eur J Orthod* 2009; **31**: 129–34. doi: <https://doi.org/10.1093/ejo/cjn088>
35. Maret D, Peters OA, Galibourg A, Dumoncel J, Esclassan R, Kahn JL, et al. Comparison of the accuracy of 3-dimensional cone-beam computed tomography and micro-computed tomography reconstructions by using different voxel sizes. *J Endod* 2014; **40**: 1321–6. doi: <https://doi.org/10.1016/j.joen.2014.04.014>