

ORIGINAL ARTICLE

Linear accuracy and reliability of volume data sets acquired by two CBCT-devices and an MSCT using virtual models: A comparative *in-vitro* studyJOHANNES WIKNER¹, HENNING HANKEN¹, CHRISTINE EULENBURG², MAX HEILAND¹, ALEXANDER GRÖBE¹, ALEXANDRE THOMAS ASSAF¹, BJÖRN RIECKE¹ & REINHARD E. FRIEDRICH¹¹Department of Oral and Maxillofacial Surgery, University Medical Center Hamburg Eppendorf, Hamburg, Germany, and ²Medical Biometry and Epidemiology, University Medical Center Hamburg Eppendorf, Hamburg, Germany**Abstract**

Objective. To discriminate clinically relevant aberrance, the accuracy of linear measurements in three-dimensional (3D) reconstructed datasets was investigated. **Materials and methods.** Three partly edentulous human skulls were examined. Landmarks were defined prior to acquisition. Two CBCT-scanners and a Quad-slice CT-scanner were used. Actual distances were physically measured with calipers and defined as a reference. Subsequently, from digital DICOM datasets, 3D virtual models were generated using maximum intensity projections (MIPs). Linear measurements were performed by semi-automated image analysis. Virtual and analogue linear measurements were compared using repeated measurements in a mixed model ($p \leq 0.05$). **Results.** No significant difference was found among all of the digital measurements when compared to one another, whereas a significant difference was found in matched-pairs analysis between CBCT and calipers ($p = 0.032$). All digitally acquired data resulted in lower mean values compared to the measurements via calipers. A high level of inter-observer reliability was obtained in the digital measurements (inter-rater correlation = 0.988–0.993). **Conclusions.** The reconstructed datasets led to highly consistent values among linear measurements. Yielding sub-millimeter precision, these modalities are assumed to reflect reality in a clinically irrelevant altered manner. During data acquisition and evaluation, a maximum of precision must be achieved.

Key Words: C-arm, computed tomography (CT), cone beam computed tomography (CBCT), maximum intensity projection (MIP), multiplanar reconstructions (MPR), three-dimensional (3D)

Introduction

Precise sterical information is crucial in diagnostic radiology and is, therefore, of vital therapeutic importance in oral- and maxillofacial surgery (OMFS). Computed tomography (CT) was previously the standard tool for visualization in three dimensions [1]. Often, however, direct physical assessment of the examined structure is not reasonable, which necessitates a generated image as a surrogate. The underlying data and resulting images should be capable of depicting bony and dental structures in exact images on a clinically reliable scale following digital processing without superimposition of neighboring textures and avoiding artifacts.

The freedom of choice in diagnostics has been substantially enhanced by the introduction of cone beam computed tomography (CBCT) as an imaging modality in OMFS in the late 1990s following Feldkamp's algorithm, which was developed more than a decade earlier [2,3]. A common argument in favor of CT is the evaluation of soft tissue [4], but, despite lower image contrast, CBCT is assumed not to be limiting in the high-contrast resolution that is needed when evaluating bony structures [2,5,6]. CBCT has proven its usefulness to numerous applications in OMFS ever since, especially for implant planning [7]. CBCT and CT are assumed to attain submillimeter accuracy for linear measurements showing generated images of highest geometrical

Correspondence: Johannes Wikner, MD, DMD, MBA (Consultant), Department of Oral and Maxillofacial Surgery, University Medical Center Hamburg-Eppendorf, Martinistraße 52, 20246 Hamburg, Germany. Tel: +49/40 7410 53259. Fax: +49/40 7410 55467. E-mail: j.wikner@uke.de
The first two authors contributed equally to this work.

(Received 20 November 2014; accepted 29 March 2015)

correctness [8,9] and volumetric assessments show a high degree of agreement [10]. Moreover, mobile cone beam devices have proven themselves in clinical applications in OMFS, providing immediately suitable information, particularly regarding postoperative results [11,12]. Although the method has been found to be more susceptible to metal artifacts than CT [13], comparable imaging quality between C-arm and CT imaging is assumed [14].

Despite differences in the underlying physical principle, the acquired volume data-sets consist of voxels as their smallest parts carrying three-dimensional (3D) information in all modalities. The manufacturer-preset voxel-sizes differ between (CBCT) devices and are assumed to have an influence on diagnostic outcomes in OMFS [15].

Cross-sectional images in multi-planar reconstructions (MPRs) are often utilized to depict 3D objects in flattened perpendicular planes, allowing digital measurements. In an attempt to acquire complete information from such objects, technical developments have enabled the creation of 3D reconstructions from CBCT or CT scans and subsequent voxel-based DICOM datasets, resulting in maximum intensity projections (MIPs).

The question of general superiority of a method in the evolving field of imaging in dentistry and OMFS is still unanswered. According to the current literature, the physicochemical properties of the devices (e.g. of the detectors, adapted reconstruction filters, optimized processing kernels, etc.) and the processing of the data seem to be quite important for reliable and reproducible information [16]. Because the surgical work flow from diagnostics, planning, intraoperative decisions and pre- and post-operative comparisons as decision points is image-based, the synchronization and comparison of images from varying sources are gaining importance.

Because the establishment of general protocols for different diagnostic tasks needs further refinement, needs-based adjustments seem to allow a more purposeful application in this context and will stimulate the process in a patient-centered manner.

Based on these considerations, we hypothesize that the dimensional accuracy of 3D reconstructions in current software based on CBCT and CT scans represents the real conditions exactly apart from the soft tissue in an attempt to minimize processing bias of the data.

Aim

The first question to be answered in this study was whether measurements in DICOM-based virtual models in a homogenized processing flow demonstrate a resilient reliability level in a feasible approach.

Second, can 3D derived measurements from varying sources match the precision of direct measurements, if

available? Third, is it possible to generate substantial differences among the methods under clinical conditions?

Herewith, we are aiming to deduce findings on a translational scale for clinical applicability in dentistry and OMFS.

Materials and methods

Three dried, macerated, adult and partly edentulous skulls were used in this *in-vitro* study. Three X-ray devices were applied: a C-arm (Arcadis Orbic 3D, Siemens Medical Solutions, Erlangen, Germany), another CBCT-Scanner (GALILEOS[®], Sirona-Dental, Bensheim, Germany) and a standard Quad-slice (4-line) CT Scanner (Philips Mx8000, Philips Healthcare, Hamburg, Germany).

We were using the same protocols as those run in clinical practice for the devices as specified herein. The dosimetry remained disregarded because this topic has been discussed frequently [17].

The C-arm was operated under a 100 kV voltage and a current of 2.3 mA. A total of 100 projections were taken. The slice thickness was 0.475 mm at a scanning time of 32 s. The single resolutions of the images of 1024 × 1024 pixels resulted in a 1 k²-solution.

The GALILEOS[®]-system was equipped with a charged couple device. The voltage amounted to 85 kV under a current of 7 mA. The radiation time was 3000 ms within a scanning time of 14 s and the field of view (FOV) was 15 cm. The voxel size amounted to 0.15 cm.

The Quad-slice CT Scanner acquired the data under a voltage of 120 kV with a current of 30 mA. The slice thickness/overlap was 1.3 mm and 0.6 mm, respectively.

Furthermore, analog measurements were performed using an orthodontic sliding caliper (REF 042-751-00, Dentaaurum[®], Munich, Germany).

The anatomical maxillary and midfacial sites were defined prior to acquisition. The landmarks were chosen to be as punctate or as delimitable as possible and to represent clinical situations, e.g. midfacial trauma and dentoalveolar procedures in OMFS. Furthermore, landmarks were chosen that enable valid comparisons with the data in recent literature. Table I lists all of the chosen landmarks, which are accentuated if the site is located within a structure, thereby preventing direct access for caliper measurement.

The group of experienced raters consisted of two senior consultants and one consultant in OMFS. Only nine landmarks were directly accessible in each of the three skulls, and they were measured with the calipers by all raters to set a standard by consensus ($n = 27$ values). The caliper measurements were designated as the dimensional truth. All digital datasets resulted in a DICOM-compatible format for

Table I. Distribution of sample sites and distances measured.

	(1) D LCI to Lower margin of left FI	(2) Min D med ORs	(3) Max. width AP	(I) Max L right C	(II) Max L left C	(III) Min D ULSM to URSM	(4) Dia left IF	(5) Dia right IF	(6) Outer D FIs	(7) Inner D IFs	(8) D between Inner border FI right and outer limit FI left	(9) Min D CZs
Skull I	+	+	+	+	+	+	+	+	+	+	+	+
Skull II	+	+	+	+	+	+	+	+	+	+	+	+
Skull III	+	+	+	X	X	X	+	+	+	+	+	+

AP, apertura piriformis; C, canine; ULSM, upper left second molar; URSM, upper right second molar; CZ, crista zygomaticoalveolaris; LCI, limbus central incisors; D, Distance; Dia, Diameter; IF, infraorbital foramen; L, length; OR, orbital rim; +, measurements possible; X, not to be found; (I-III), direct measurement not possible.

further analysis. OsiriX™ (v5.8.2.) was used to allow inspection and exploration of the resulting MIPs as 3D-images, thus facilitating the dynamic adjustment of point-to-point lines for the rater. Hence, the images were viewed at full dynamic window level and linear opacity was set. Three time points were set across a 14-day interval for digital measurements by all three raters and 12 landmarks were evaluated ($n = 891$ values in total, 297 values per skull and modality). Figure 1 shows sample aspects of the semi-automated measurements.

Statistical analysis

For statistical testing, we used SPSS (SPSS for Windows, version 21.0, 2012, SPSS Inc., Chicago, IL).

Statistical graphs were produced using stata software (Stata/SE version 13.1, 2014, StataCorp LP, College Station, TX). To compare the measurements from different modalities, a linear mixed model analysis was performed, controlling for random effects such as rater, skull and sample site. The level of significance was 5%. Reliability was tested via inter-rater correlation coefficients. Bland-Altman-Plots were computed to assess the consistency between the measurement methods graphically.

Results

The results for the respective devices can be found in Table II. Examining the complete dataset of all landmarks to evaluate specific differences between

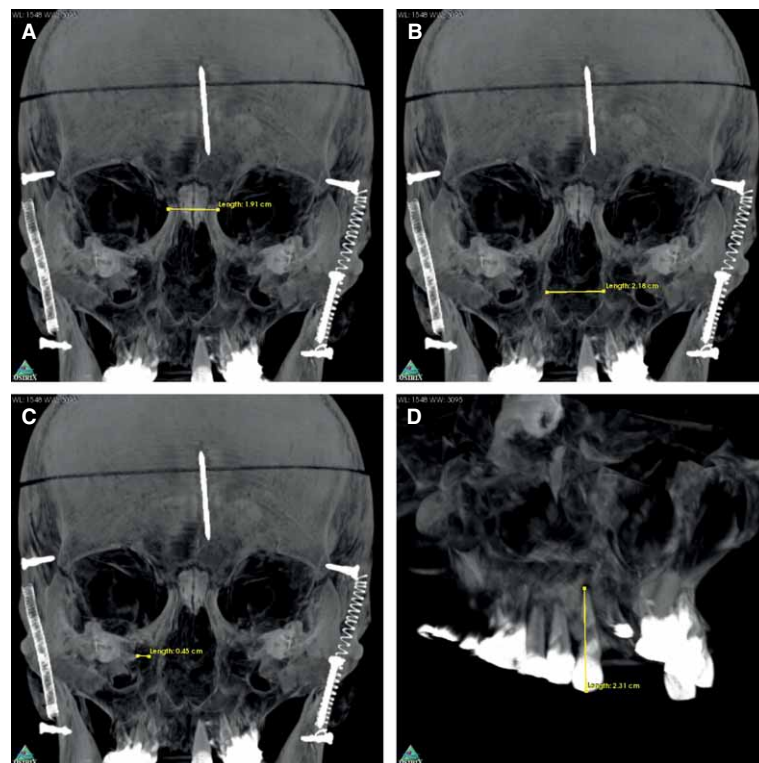


Figure 1. Measurements in MIP reconstructions using OsiriX®. (A) Minimum distance of medial orbital walls; (B) Maximum width of apertura piriformis; (C) Diameter of infraorbital foramen; (D) Length of upper right canine.

Table II. Estimation of the devices.

Method	Mean value	<i>n</i>	Standard deviation (mm)
Caliper	3.5938	81	2.015,80
CT	3.3573	297	1.952,28
CBCT	3.3095	297	1.946,49
C - arm	3.3532	297	1.953,53
Total	3.3612	972	1.954,57

devices, the highest mean value was found for the caliper measurements with 3.5938 mm and a SE of 2.0158. The measurements by the other devices showed mean values from 3.3095–3.3573 mm and a SE between 1.94649–1.95353 mm.

In matched pairs analysis (Table III), significant differences between the digital measurements in MIP reconstructions of the CBCT images and the analog measurements with the calipers were found ($p = 0.032$) with smaller mean values for the digital assessments. No significant differences in the matched pairs analysis were found between the digitally processed CT and C-arm datasets and the caliper measurements ($p > 0.133$ to $p < 0.898$).

The mean deviations of the caliper measurements are given in percentages in Figure 2. The highest deviation was noted in measurements of the distance from the limbus of the central incisors to the lower margin of the left infraorbital foramen, the minimal distance between both medial orbital rims and the diameter of the left infraorbital foramen (see Table I). Examining the absolute standard deviations, the highest values exceeding 1 mm were found for the same sites, whereas all other standard deviations stayed below 1 mm.

Figure 3 shows the distribution of all measurements made from the CT-based data, CBCT data and

C-arm data. For the CT and C-arm measurements, 3.37% of the values were outside the 95% limit of agreement (−0.397 and 0.406), showing sub-millimeter precision for most landmarks. In a comparison of CT and CBCT, 4.38% of the values were outside the 95% limit of agreement (−0.443 and 0.538).

Figure 4 shows the distribution of all measurements made from CBCT-based data in comparison with the data from the calipers. Here, the measurements for the minimum distance of the medial orbital wall are outside the limits of agreement with a mean difference of −0.154 mm (−1.066 to 0.757).

The inter-rater analysis showed a correlation of 0.993 for C-arm, 0.99 for CT and 0.988 for CBCT.

Discussion

No general imaging protocol has yet been defined for diagnostic purposes in dentistry and OMFS at the current stage. The need for standardization is evident [15,16]. Despite their maximal flexibility, analog measurements cannot be claimed as the gold standard for sub-surface structures.

In all 3D reconstructions, strict rectangularity of the reconstructed images must be ensured to achieve reliable measurements [18]. To overcome the limitations of cross-sectional imaging derived from varying sources, our alternative approach presented in this study included three-dimensional measurements in MIP images in direct comparison to analog caliper assessments. We hypothesized that measurements in MIP reconstructions are as precise and reliable as those of calipers. In contrast, this study showed significant differences between the caliper measurements and those from MIP reconstructions based on CBCT datasets, with smaller mean values for

Table III. Matched pairs analysis.

Device I	Device II	Difference in mean values (mm; I–II)	SE (mm)	Degrees of freedom	Significance ^c	95% CI of difference	
						Lower	Upper
Caliper	C-arm	0.068	0.052	954.194	0.189	−0.034	0.171
	CT	0.064	0.052	954.194	0.217	−0.038	0.167
	CBCT	0.112	0.052	954.194	0.032	0.010	0.214
C-arm	Caliper	−0.068	0.052	954.194	0.189	−0.171	0.034
	CT	−0.004	0.032	953.000	0.898	−0.066	0.058
	CBCT	0.044	0.032	953.000	0.169	−0.019	0.106
CT	Caliper	−0.064	0.052	954.194	0.217	−0.167	0.038
	C-arm	0.004	0.032	953.000	0.898	−0.058	0.066
	CBCT	0.048	0.032	953.000	0.133	−0.015	0.110
CBCT	Caliper	−0.112	0.052	954.194	0.032	−0.214	−0.010
	C-arm	−0.044	0.032	953.000	0.169	−0.106	0.019
	CT	−0.048	0.032	953.000	0.133	−0.110	0.015

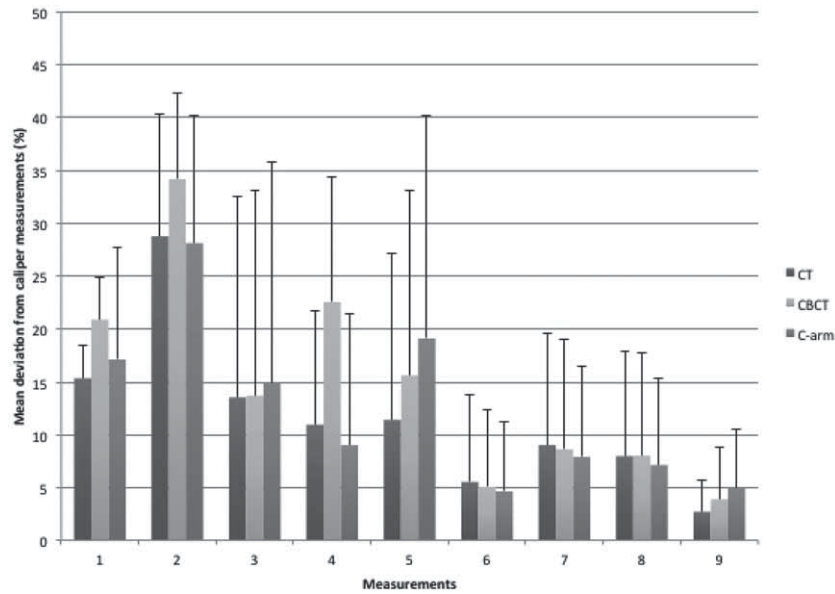


Figure 2. Mean deviations of virtual measurements made in CT, CBCT and C-arm compared to caliper measurements (%). For sites of measurements (1–9) see Figure 1.

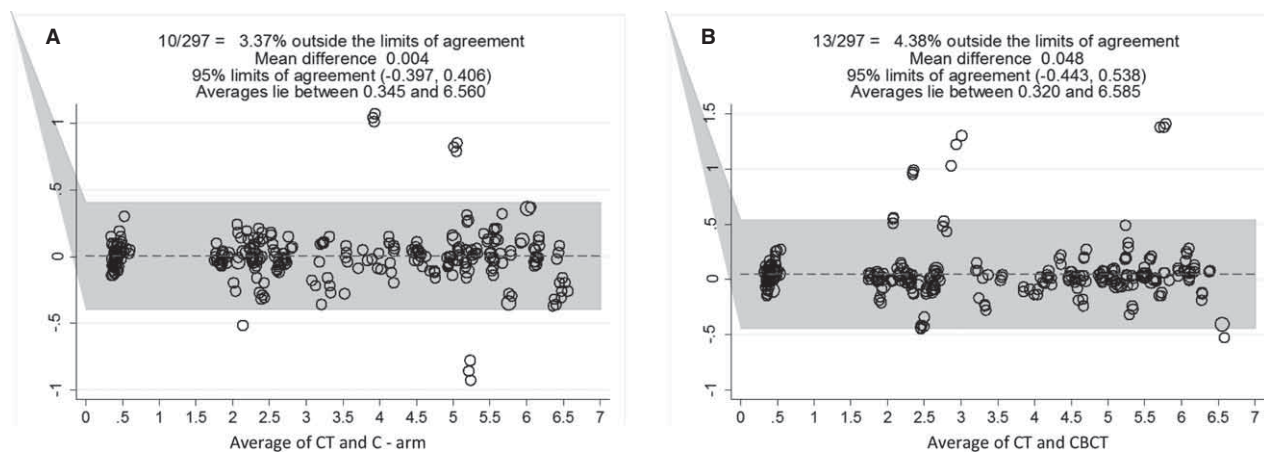


Figure 3. Bland Altman plots of comparisons between (A) CT and C – arm and (B) CT and CBCT.

the digital assessments. All of the digitally acquired data showed high consistency with no significant differences.

A comparison between measurements in CBCT or CT scans and caliper measurements has been described before with inconsistent results [19,20]. These inconsistencies can be explained by methodical differences such as different sample sites, inclusion of soft tissue landmarks and measurements in MPR images [21–24]. Today, a variety of algorithms are used for reconstructing cross-sectional images from acquired volumetric data [25,26].

Deducible density values in commonly utilized data diverge on a statistically significant scale when comparing CBCT with CT, thus complicating methodological comparisons. However, a correlation between voxel-values and Hounsfield units (HU) is assumable [27,28], but it might partly explain the inconsistencies

in the current literature with regard to linear measurements. Using MIPs for visualization of defined landmarks for the purpose of linear measurements seems valid and provides evaluable images.

In a comparison of real anatomic measurements via digital calipers and measurements in MPR reconstructions of CBCT scans, Dalessandrinni et al. [21] found statistically significant differences in only a few cases with positive and negative deviations. In this context, Lund et al. [29] suggested the possibility of minor distortions in 3D reconstructions based on CBCT scans. In contrast to the findings of Lund et al., our findings demonstrated significant differences in analog vs digital measurements when comparing 3D MIP reconstructions based on CBCT datasets. The caliper measurements were on average higher than the measurements in the virtual model. This finding may be partly explained by the fact that,

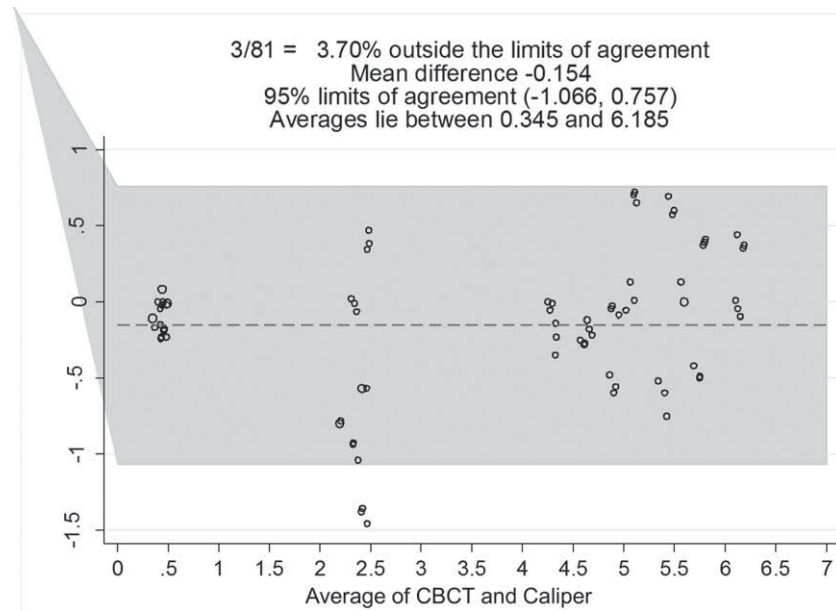


Figure 4. Bland Altman plot of comparison between CBCT and calipers.

in MIP reconstructions, parts of the skull are visible that cannot be seen while using the calipers such as the posterior and narrow parts of the infraorbital foramen.

Berco et al. [20] utilized dry skulls analogously to our study, but defined different landmarks. As in the present study, highly consistent measurements in CBCT scans were found by Berco et al., with no effect of the orientation of the skulls on accuracy. Furthermore, additional varying results comparing analog and digital measurements have been found. This result might be due to using 0.5 mm metal bearings as landmarks, which are not as punctate as anatomical landmarks, thus hindering precise measurements. The inconsistency of the landmarks used in the available literature might be the main reason for these inconsistent conclusions.

Consistent with our own findings, Lascala et al. [24] described significant differences in measurements in CBCT MPR reconstructions that were under-estimations, especially at points set at the skull base. Through assessing landmarks in MIP reconstructions, this effect can still be found, as described in our study. In addition to this finding, the exact definition of landmarks without the insertion of sterical objects (e.g. metal bearings or points) seems to be crucial. Sterical objects are inappropriate for measuring small distances because the clear definition of distinct points on the objects, especially in MPR reconstructions, is difficult. Anatomical structures should be used instead, e.g. the infraorbital foramen [30].

In this study, the chosen landmarks were set at clearly depictable and comprehensible anatomical structures in the midface that are relevant for clinical diagnostic and therapeutic purposes (e.g. width of the

orbit and infraorbital foramen in fracture diagnostics). Differences in measurements were found between caliper and digital assessments of the sites. The extent of these differences was largest for measuring landmarks that are funnel-shaped, such as the orbit or the infraorbital foramen. This specific anatomic feature may cause an over-estimation of the outer diameter in caliper measurements. In contrast, no significant differences were found between the digital measurements in MIP reconstructions.

In contrast to our findings, an association with a clinically and statistically significant measurement error in CT and CBCT was found by Al-Ekrish and Ekram [19], whose CBCT measurements were significantly more accurate than those of CT. These findings can also be explained by methodical differences, e.g. MPR reconstructions were used for measurements and different reconstruction software was used in an intermediate step to ensure similar reconstructions. The authors emphasized that, despite repeated attempts to set a standardized plane for the measurements, the orientation was most challenging, which strengthens our decision to decouple the assessments from strict planes. Furthermore, the study described a degree of operator dependency in CBCT measurements.

Operator dependency could be a reason for the significant difference between CBCT and analog measurements in the present paper. The possibility of elusive deviations with an impact on statistically feasible but random differences should be emphasized.

Considering conceivable explanatory variables, the influence of different reconstruction protocols should be noted. At the current stage, this influence must be stated as inconclusive. Brown et al. [25] examined CBCT and analog measurements in a

comparative study. Those authors found no differences for measurements in CBCT scans reconstructed with different reconstruction protocols. A comparative setting aiming for these potential effects is not available and should be addressed in further studies. Hence, the chosen method in our study of reconstructing MIPs out of primary DICOM data should be considered as the appropriate approach. Regarding the choice of software (OsiriX™), we evaluated its analytical consistency to be worthwhile and sufficient on a clinical scale. The use of one software solution for the evaluation of images acquired by different modalities is mandatory for comparison of the data.

Gaia et al. [31] compared two imaging software programs in a study published in 2013. OsiriX™ was found to be unsuccessful at producing accurate linear measurements for Le Fort I osteotomy compared to measurements via calipers. In the described study, the definition of osteotomy lines and bony landmarks was difficult, as discussed by the authors, and could have led to this result.

Furthermore, in comparing our results with recent literature, another fact must be elucidated. The chosen radiological devices, either within one study or between similar study designs, belong to different model generations; therefore, their efficiency varies. Early attempts stating reliability and accuracy in favor of a modality are conditional on recent findings. High-performing modern devices must not be regarded as interchangeable with older ones. For example, Blendl et al. [32] found geometric accuracy to be higher in CBCT than in CT. A reason could be seen in the higher xyz-resolution of the chosen systems, which in turn makes the statement self-fulfilling.

A study by Hofmann et al. [33] examined the use of spiral CT and CBCT for measuring teeth, in which CT reconstructions were described to be statistically significantly more precise than CBCT reconstructions. In our study, no significant differences between the two modalities were found, which may be explained by the use of a 4-line MSCT for acquisition of our data in contrast to the 64-line CT in the study by Hofmann et al. In terms of radiation exposure, our set-up with a 4-line CT seems to be a more realistic diagnostic approach for clinical routines, despite considerable advantages in depicting reality in an unaltered manner. For instance, Kamiyama et al. [34] found no effect on the measurement accuracy of different mandibular positioning or pitch factor using a 64-line CT. This fact seems to be rather negligible when using MIPs, which opens up new horizons when assessing reliability and accuracy in comparisons of various methods.

Reasonable application in clinical routine must be considered separately from *ex-vivo* examinations. At the current stage, exposure to radiation should still be

noted as a central aspect of meaningful application in clinical settings. In this context, CBCT scanners were found to be an alternative to CT at comparable radiation exposure [35,36]. Moreover, choosing larger voxel sizes might be acceptable for reducing the radiation dose while still providing high resolution linear measurements in CBCT scans [37]. Considering these statements for established cross-sectional imaging, our results suggest that equipotent and comparable MIPs can be achieved for clinical evaluation without relevant information loss.

Variations in voxel size, the influence of the applied radiation and potential increased faultiness in measurements due to metallic artifacts in CBCT [38,39] were avoided in our study due to the chosen specimens and the data processing. This topic should be addressed in further studies.

In summary, measurements in 3D MIP reconstructions are sufficiently precise and accurate from a clinical point of view and depict the real situation quite accurately. Image quality depends on the applied voltage and current, the technical properties of the detector and the reconstruction kernel, which are specific and only conditionally adaptable in different devices.

However, different 3D imaging modalities such as CT and C-arm seem not to have an impact on the accuracy of the resulting MIP virtual models. CBCT MIP reconstructions may depict the real situation as smaller on a statistically tangible level, with a maximum of comparability in processing DICOM-data sets.

Conclusions

Sub-millimeter precision was attainable in the acquired data sets with a maximum of inter-rater agreement. Despite isolated significant differences in analog vs digital measurements, these factors should be assumed to be of minor relevance on a clinical scale. In assessments of linear accuracy, the selection of landmarks might cause altered values in different devices, which might distort the analysis. Furthermore, DICOM-derived 3D imaging using MIPs seems to be a promising imaging modality for depicting midfacial and dental structures on a reliable scale and allowing a virtual model, which can be manipulated. Thus, some of the limitations of cross-sectional imaging can be overcome.

Under clinical conditions—made challenging by diminished accessibility of chosen landmarks in sub-surface structures—the applicability of reconstructed three-dimensional MIP models in maxillofacial surgery for diagnostic and therapeutic means is given. Further studies should use only one program for image reconstruction, because measurements from different software solutions seem to diminish the comparability of the acquired data.

Declaration of interest: M. Heiland received consultation fees from the imaging company Siemens Medical Solutions. The other authors declare no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

References

- [1] Kamrun N, Tetsumura A, Nomura Y, Yamaguchi S, Baba O, Nakamura S, et al. Visualization of the superior and inferior borders of the mandibular canal: a comparative study using digital panoramic radiographs and cross-sectional computed tomography images. *Oral Surg Oral Med Oral Pathol Oral Radiol* 2013;115:550–7.
- [2] Arai Y, Tammissalo E, Iwai K, Hashimoto K, Shinoda K. Development of a compact computed tomographic apparatus for dental use. *Dentomaxillofac Radiol* 1999;28:245–8.
- [3] Feldkamp LA, Davis LC, Kress JW. Practical Cone-Beam Algorithm. *J Opt Soc Am A* 1984;1:612–19.
- [4] Hatcher DC. CT & CBCT imaging: Assessment of the orbits. *Oral Maxillofac Surg Clin North Am* 2012;24:537–43.
- [5] Lofthag-Hansen S, Grondahl K, Ekestubbe A. Cone-beam CT for preoperative implant planning in the posterior mandible: Visibility of anatomic landmarks. *Clin Implant Dent Relat Res* 2009;11:246–55.
- [6] Apostolakis D, Brown JE. The anterior loop of the inferior alveolar nerve: Prevalence, measurement of its length and a recommendation for interforaminal implant installation based on cone beam CT imaging. *Clin Oral Implants Res* 2012;23:1022–30.
- [7] Tyndall DA, Price JB, Tetradis S, Ganz SD, Hildebolt C, Scarfe WC. Position statement of the American Academy of Oral and Maxillofacial Radiology on selection criteria for the use of radiology in dental implantology with emphasis on cone beam computed tomography. *Oral Surg Oral Med Oral Pathol Oral Radiol* 2012;113:817–26.
- [8] Loubele M, Van Assche N, Carpentier K, Maes F, Jacobs R, van Steenberghe D, et al. Comparative localized linear accuracy of small-field cone-beam CT and multislice CT for alveolar bone measurements. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2008;105:512–18.
- [9] Marmulla R, Wörtche R, Mühling J, Hassfeld S. Geometric accuracy of the NewTom 9000 Cone Beam CT. *Dentomaxillofac Radiol* 2005;34:28–31.
- [10] Ahlowalia MS, Patel S, Anwar HM, Cama G, Austin RS, Wilson R, et al. Accuracy of CBCT for volumetric measurement of simulated periapical lesions. *Int Endod J* 2013;46:538–46.
- [11] Heiland M, Schmelzle R, Hebecker A, Schulze D. Intraoperative 3D imaging of the facial skeleton using the SIREMOBIL Iso-C3D. *Dentomaxillofac Radiol* 2004;33:130–2.
- [12] Heiland M, Schulze D, Blake F, Schmelzle R. Intraoperative imaging of zygomaticomaxillary complex fractures using a 3D C-arm system. *Int J Oral Maxillofac Surg* 2005;34:369–75.
- [13] Heiland M, Schulze D, Adam G, Schmelzle R. 3D-imaging of the facial skeleton with an isocentric mobile C-arm system (Siremobil Iso-C3D). *Dentomaxillofac Radiol* 2003;32:21–5.
- [14] Pohlenz P, Blessmann M, Oesterhelweg L, Habermann CR, Begemann PG, Schmidgunst C, et al. 3D C-arm as an alternative modality to CT in postmortem imaging: technical feasibility. *Forensic Sci Int* 2008;175:134–9.
- [15] Spin-Neto R, Gottfredsen E, Wenzel A. Impact of voxel size variation on CBCT-based diagnostic outcome in dentistry: A systematic review. *J Digit Imaging* 2013;26:813–20.
- [16] Spin-Neto R, Marcantonio E Jr, Gottfredsen E, Wenzel A. Exploring CBCT-based DICOM files. A systematic review on the properties of images used to evaluate maxillofacial bone grafts. *J Digit Imaging* 2011;24:959–66.
- [17] Angelopoulos C, Scarfe WC, Farman AG. A comparison of maxillofacial CBCT and medical CT. *Atlas Oral Maxillofac Surg Clin North Am* 2012;20:1–17.
- [18] Tyndall DA, Brooks SL. Selection criteria for dental implant site imaging: A position paper of the American Academy of Oral and Maxillofacial radiology. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2000;89:630–7.
- [19] Al-Ekrish AA, Ekram M. A comparative study of the accuracy and reliability of multidetector computed tomography and cone beam computed tomography in the assessment of dental implant site dimensions. *Dentomaxillofac Radiol* 2011;40:67–75.
- [20] Berco M, Rigali PH Jr, 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;136:17 e1–9; discussion 17–8.
- [21] Dalessandri D, Bracco P, Paganelli C, Hernandez Soler V, Martin C. Ex vivo measurement reliability using two different cbct scanners for orthodontic purposes. *Int J Med Robot* 2012;8:230–42.
- [22] Kamburoglu K, Kolsuz E, Kurt H, Kilic C, Ozen T, Paksoy CS. Accuracy of CBCT measurements of a human skull. *J Digit Imaging* 2011;24:787–93.
- [23] Chen LC, Lundgren T, Hallstrom H, Chere F. Comparison of different methods of assessing alveolar ridge dimensions prior to dental implant placement. *J Periodontol* 2008;79:401–5.
- [24] Lascala CA, Panella J, Marques MM. Analysis of the accuracy of linear measurements obtained by cone beam computed tomography (CBCT-NewTom). *Dentomaxillofac Radiol* 2004;33:291–4.
- [25] Brown AA, Scarfe WC, Scheetz JP, Silveira AM, Farman AG. Linear accuracy of cone beam CT derived 3D images. *Angle Orthod* 2009;79:150–7.
- [26] Park JC, Song B, Kim JS, Park SH, Kim HK, Liu Z, et al. Fast compressed sensing-based CBCT reconstruction using Barzilai-Borwein formulation for application to on-line IGRT. *Med Phys* 2012;39:1207–17.
- [27] Mah P, Reeves TE, McDavid WD. Deriving Hounsfield units using grey levels in cone beam computed tomography. *Dentomaxillofac Radiol* 2010;39:323–35.
- [28] Cassetta M, Stefanelli LV, Pacifici A, Pacifici L, Barbato E. How accurate is CBCT in measuring bone density? A comparative CBCT-CT in vitro study. *Clin Implant Dent Relat Res* 2014;16:471–8.
- [29] Lund H, Grondahl K, Grondahl HG. Accuracy and precision of linear measurements in cone beam computed tomography Accutomo tomograms obtained with different reconstruction techniques. *Dentomaxillofac Radiol* 2009;38:379–86.
- [30] Naji P, Alsufyani NA, Lagravere MO. Reliability of anatomic structures as landmarks in three-dimensional cephalometric analysis using CBCT. *Angle Orthod* 2014;84:762–72.
- [31] Gaia BF, Pinheiro LR, Umetsubo OS, Costa FF, Cavalcanti MG. Comparison of precision and accuracy of linear measurements performed by two different imaging software programs and obtained from 3D-CBCT images for Le Fort I osteotomy. *Dentomaxillofac Radiol* 2013;42:20120178.
- [32] Blendl C, Fiebich M, Voigt JM, Selbach M, Uphoff C. [Investigation on the 3 D geometric accuracy and on the image quality (MTF, SNR and NPS) of volume tomography units (CT, CBCT and DVT)]. *Rofo* 2012;184:24–31.
- [33] Hofmann E, Medelnik J, Fink M, Lell M, Hirschfelder U. Three-dimensional volume tomographic study of the imaging accuracy of impacted teeth: MSCT and CBCT comparison-an in vitro study. *Eur J Orthod* 2013;35:286–94.
- [34] Kamiyama Y, Nakamura S, Abe T, Munakata M, Nomura Y, Watanabe H, et al. Linear measurement accuracy of dental

- CT images obtained by 64-slice multidetector row CT: The effects of mandibular positioning and pitch factor at CT scanning. *Implant Dent* 2012;21:496–501.
- [35] Kyriakou Y, Kolditz D, Langner O, Krause J, Kalender W. [Digital volume tomography (DVT) and multislice spiral CT (MSCT): An objective examination of dose and image quality]. *Rofo* 2011;183:144–53.
- [36] Leary D, Robar JL. CBCT with specification of imaging dose and CNR by anatomical volume of interest. *Med Phys* 2014; 41:011909.
- [37] Moshfeghi M, Tavakoli MA, Hosseini ET, Hosseini AT, Hosseini IT. Analysis of linear measurement accuracy obtained by cone beam computed tomography (CBCT-New-Tom VG). *Dent Res J (Isfahan)* 2012;9:S57–62.
- [38] Schulze RK, Berndt D, d’Hoedt B. On cone-beam computed tomography artifacts induced by titanium implants. *Clin Oral Implants Res* 2010;21:100–7.
- [39] Schulze R, Heil U, Gross D, Bruellmann DD, Dranischnikow E, Schwanecke U, et al. Artefacts in CBCT: a review. *Dentomaxillofac Radiol* 2011;40:265–73.