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Head motion during cone-beam computed tomography: Analysis of frequency and influence on image quality

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ABSTRACT

Purpose: Image artifacts caused by patient motion cause problems in cone-beam computed tomography (CBCT) because they lead to distortion of the 3-dimensional reconstruction. This prospective study was performed to quantify patient movement during CBCT acquisition and its influence on image quality.

Materials and Methods: In total, 412 patients receiving CBCT imaging were equipped with a wireless head sensor system that detected inertial, gyroscopic, and magnetometric movements with 6 dimensions of freedom. The type and amplitude of movements during CBCT acquisition were evaluated and image quality was rated in 7 different anatomical regions of interest. For continuous variables, significance was calculated using the Student t-test. A linear regression model was applied to identify associations of the type and extent of motion with image quality scores. Kappa statistics were used to assess intra- and inter-rater agreement. Chi-square testing was used to analyze the impact of age and sex on head movement.

Results: All CBCT images were acquired in a 10-month period. In 24% of the investigations, movement was recorded (acceleration: >0.10 [m/s^2]; angular velocity: >0.018 [°/s]). In all examined regions of interest, head motion during CBCT acquisition resulted in significant impairment of image quality ($P<0.001$). Movement in the horizontal and vertical axes was most relevant for image quality ($R^2>0.7$).

Conclusion: Relevant head motions during CBCT imaging were frequently detected, leading to image quality loss and potentially impairing diagnosis and therapy planning. The presented data illustrate the need for digital correction algorithms and hardware to minimize motion artefacts in CBCT imaging. ***(Imaging Sci Dent 2020; 50: 227-36)***

KEY WORDS: Cone-Beam Computed Tomography; Diagnostic Imaging; Motion; Artifacts

Introduction

Cone-beam computed tomography (CBCT) is a well-established three-dimensional (3D) radiographic diagnostic tool for oral and maxillofacial tasks.[1-3] In addition to its widespread availability, another advantage of CBCT imaging is its lower radiation dose than that of classical computed tomography (CT).[4-6] As with other volumetric radiographic instruments, patients' movements during acquisition may result in motion artifacts that impair image quality.[4,7,8] This can be explained by the CBCT reconstruction algorithm, because if movement of the object occurs, the algorithm causes back-projection of pixels representing the same area of interest into different positions.[2,9-11] This results in cloudy images with blurred lines, double contours, and overall reduced sharpness.[8,9,12,13]

The patient's position during recording is decisive in terms of later negative influences on image quality. CBCT scans can be acquired with patients in different positions. Indeed, CBCT hardware that allows for image acquisition in a standing or sitting position requires less space, mak-

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ing such hardware particularly attractive for dental, orthodontic, and maxillofacial units.[14-16] However, a standing or sitting position leaves space for involuntary motion, resulting in image artifacts.[5,16] Another factor influencing the occurrence of artifacts is the acquisition time, which may vary from 5 to 40+ seconds depending on the device.[8]

Bontempi et al.[17] evaluated the effect of various positions in CBCT on movement-caused artifacts and found that an upright position of the patient led to a significantly higher frequency of head motions and impaired image quality. Several other publications have dealt with the systematic detection of movement and its effects. Those trials were often based on phantom data or simulations with reference motions, and therefore did not provide quantitative information about clinically relevant aspects of real motion artifacts in CBCT.[18-20] While some *in vivo* studies have investigated head motion during CBCT acquisition, differences in methodologies and varying cohort sizes make it difficult to compare the reported data.[13,21-24]

As a contribution to this topic, the primary aim of this study was to analyze head movements during CBCT imaging and their influence on image quality in the standing position. Therefore, 1) the general occurrence of movement, 2) the nature of the movement (rotation, translation), and 3) the extent of movement (amplitude, velocity) were measured to describe clinically relevant aspects of head motion during CBCT acquisition. Furthermore, the occurrence and extent of movements were correlated with image quality of the CBCT acquisitions.

Materials and Methods

Patients

During a period of 10 months, 412 patients were recruited for this prospective single-center clinical study. All patients treated at the Department of Oral, Dental and Maxillofacial Diseases of University of Heidelberg referred for CBCT imaging who agreed to participate were included. The exclusion criteria were patients under the age of 18 and those with fresh head injuries or a history of hemi-craniectomy making it impossible to fix the necessary sensors. General diseases including Parkinson disease, hyperthyroidism, and multiple sclerosis were noted. This clinical trial followed the tenets of the Declaration of Helsinki regarding medical protocols and ethics and was approved by the ethics committee of the medical faculty of the University of Heidelberg (ethics vote: S-151/2013). Written informed consent was provided by all patients included in the study.

CBCT acquisition

All CBCT acquisitions were performed using GALILEOS Comfort (98 kV at 3-8 mA pulsed operation, spherical volume of 15.4 cm, scanning time of 14 s, isotopic voxel size of 0.25 mm; Sirona, Bensheim, Germany). All data acquisition followed the standardized, routine protocol used in our unit: during the scan, patients were in a standing position with the head in its natural position, stabilized by a head-and chin support.

Measurement of head motions

Head motions were detected by an inertial microelectromechanical system (Colibri Wireless - Inertial Motion Tracker, Trivisio, Trier, Germany) fixed by a tight headband (Fig. 1). The wireless sensor recorded acceleration ($a = dx^2/dt^2$ in $[m/s^2]$) and angular velocity ($\omega = d\phi/dt$ in $[°/s]$) in 3 dimensions, respectively, resulting in an overall number of 6 dimensions of freedom (DOF). Only data in the time frame of the CBCT acquisition were analyzed, with a time resolution of 100 Hz and a spatial resolution of 0.1°. The sensor was linked to the CBCT device by a coupling switch for synchronization.

Definition of movement

The acceleration of the patients' heads was recorded relative to gravity. As an example, angular velocity readings on the x-axis for 2 patients during CBCT acquisition are shown in Figure 2. In cases of significant angular motion, the amplitude exceeded the regular noise level and the motion was detected by the sensor. Signal variation exceeding $\sqrt{2}$ standard deviations ($\sqrt{2}$-sigma) for each

Fig. 1. Inertial microelectromechanical sensor fixed by a tight headband on a colleague's head.

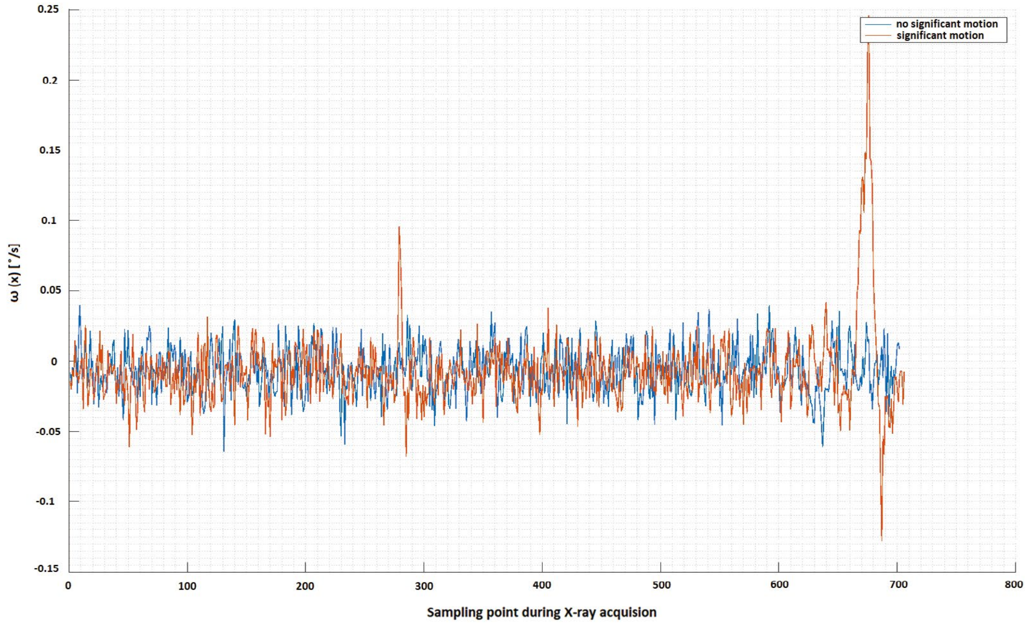

Fig. 2. Example of 2 sensor records with (orange) and without (blue) significant angular velocities during cone-beam computed tomography acquisition.

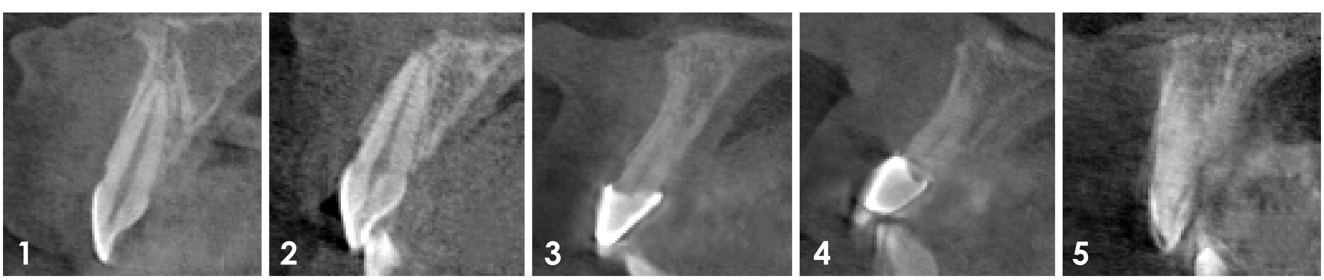

Fig. 3. Image quality scores, ranging from 1 (best) to 5 (worst), demonstrated by reference to the pulp-dentin border of tooth 11/21.

DOF was defined as patient motion. Figure 2 exemplifies the procedure (angular velocity in the x-axis of the patient with motion was 1.63 times higher than in the patient without motion).

Baseline measurement

Since this type of sensor shows a typical amount of background noise, 22 acquisitions were carried out with the sensor in a static position of the sensor and were subsequently used as a baseline reference.

Image quality scores

The image quality was evaluated by examining 7 different regions of interest (ROIs): 1) the mental foramen, 2) the structure of the mental trabecular bone, 3) the mandibular canal, 4) the pulp-dentin border of the maxillary central front teeth, 5) the periodontal space of the maxillary central front teeth, 6) the hard palate, and 7) the septum of the nose.

The ROIs were analyzed and image quality was rated using a 5-point score. The following criteria were evaluated: edge sharpness, the amount of blurring, the contrast between bone and teeth, the contrast between bone and soft tissue, and the delineation of small structures. Scores were assigned for image quality rating as follows: 1 = optimal quality; 2 = slight limitation of quality without impairment of diagnosis; 3 = slight limitation of quality with possible impairment of diagnosis; 4 = substantial limitation of diagnosis; and 5 = image not interpretable.

The scoring was performed by 2 blinded investigators (oral and maxillofacial surgeons with experience in CBCT interpretation) via Osirix v. 5.8.5 64-bit (Pixmeo SARL, Bernex, Switzerland). Figure 3 exemplifies the procedure for the pulp-dentin border of the maxillary central front teeth.

Statistical analysis

Statistical analysis was performed using SPSS version 21.0 (IBM, Armonk, NY, USA) and Microsoft Excel 2013 (Microsoft, Redmond, WA, USA). Graphical illustrations and the Pearson product-moment correlation coefficient were generated using MATLAB R2015b (MathWorks Inc., Natick, MA, USA). The significance of continuous variables was calculated by using the Student t-test, the U-test, or the Kruskal-Wallis test. Interobserver agreement was assessed by kappa statistics. Mean values were compared using the Student t-test and the Bonferroni correction was used to adjust the levels of significance for *P* values. Categorical data were checked using the chi-square test. A value of $P<0.05$ was considered to indicate statistical significance.

Results

Patients

In total, 412 patients were included in the study, of whom 235 (57%) were men and 177 (43%) were women, with a mean age of 38 years (range: 18-68 years).

Of the investigated cohort, 58 patients (14%) showed the following general diseases (isolated or in combination): hypertension (n=33), diabetes mellitus (n=27), Parkinson disease (n=2), multiple sclerosis (n=2), and hyperthyroidism (n=1).

Registered head motions

In 99 of the 412 patients (24%) linear acceleration and/or angular velocity readings were detected. Accordingly, in 313 patients (76%), no motions of the head beyond the border of √2-sigma could be detected during the acquisition of the CBCT scan.

In 7 cases, only an isolated linear acceleration was detected, whereas in 73 cases, an angular velocity was observed. Figures 4 and 5 illustrate the standard deviations of the acceleration and the angular velocity measurements of all patients compared to the reference values. In 19 cases, a combination of linear acceleration and rotation could be detected.

In 58 cases, the head motion was limited to 1 axis. Head movements in 2 dimensions were detected in 21 patients, in 3 dimensions in 9 patients, in 4 dimensions in 5 patients, in 5 dimensions in 5 patients, and in all 6 dimensions in 1 case.

Image quality scores

The mean image quality scores for the different ROIs differed significantly (Student t-test: $P<0.001$) and ranged from 2.51 (mental foramen, best quality) to 3.13 (hard palate, worst quality). Table 1 presents the mean

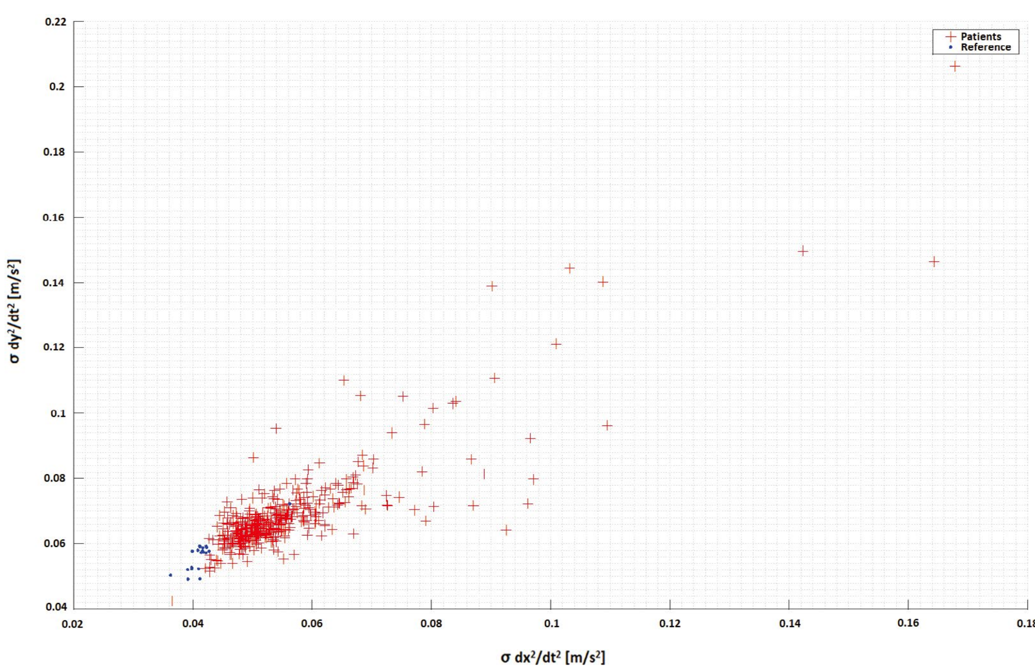

Fig. 4. Standard deviations of the angular velocity measurements of all patients (red - patients) compared with the reference measurements (blue - zero reference).

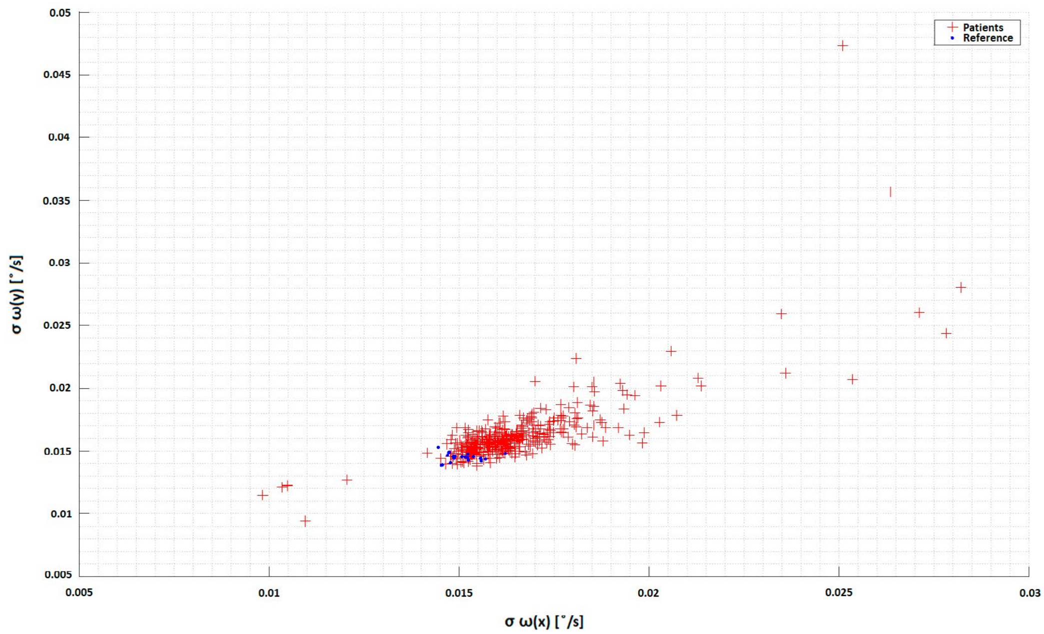

Fig. 5. Standard deviations of the acceleration measurements of all patients (red - patients) in comparison with the reference measurements (blue - zero reference).

Table 1. Mean image score values for different regions of interest with 95% CIs

Regions of interest	Mean score value	Standard deviation	95% CI	*P* value
Mental foramen	2.51	1.07	2.32-27.0	<0.001
Trabecular bone	2.64	1.16	2.44-2.85	<0.001
Mandibular canal	2.74	1.07	2.55-2.93	<0.001
Pulp-dentin border	2.91	1.17	2.70-3.11	<0.001
Periodontal space	3.04	1.28	2.81-3.26	<0.001
Hard palate	3.13	0.94	2.96-3.29	<0.001
Nasal septum	2.80	1.14	2.60-3.00	<0.001

values for the different regions of interest. The Bonferroni correction was used to adjust the level of significance for *P* values (t-test for the 7 ROIs: $P=0.007$). The overall inter-rater agreement was good (mean: 0.77) for all 7 ROIs (mental foramen: 0.76; trabecular bone: 0.74; mandibular canal: 0.83; border pulp-dentin: 0.85; periodontal space: 0.79; hard palate: 0.68; nasal septum: 0.75). Intra-rater agreement was assessed for both observers and provided good results (observer 1: 0.82; observer 2: 0.79).

The mean image quality scores of patients who showed a level of movement above the preliminarily determined cut-off of $\sqrt{2}$-sigma (acceleration: >0.10 [m/s^2]; angular velocity: >0.018 [°/s] were significantly worse than those of patients with movement below the cut-off (chi-square testing: $P<0.01$; Figs. 6 and 7).

Our analysis revealed no significant association of age and sex with the prevalence and extent of relevant head movement, although there was a tendency towards more movement in older patients (Table 2).

Table 2. Correlation analysis of age and sex with patient movement (chi-square testing)

Characteristics		No movement	Movement	*P* value
Sex	Female	44 (24.9%)	133 (75.1%)	0.192
	Male	87 (37.0%)	148 (63.0%)	
Age	18-30 years	64 (35.5%)	116 (64.5%)	0.157
	30-50 years	57 (46.0%)	67 (54.0%)	
	>50 years	23 (21.3%)	85 (78.7%)	

Linear regression analysis was conducted to determine the association of the extent of movement in various DOFs with the image quality scores in each region of interest. In all investigated ROIs and for both types of movement, the overall regression model was significant (R^2=0.06-0.8, P=<0.001-0.005). For all investigated regions and DOFs, the extent of motion was a predictor of image quality scores. The observed associations varied among different ROIs, indicating a different magnitude of influence on image quality in different ROIs. The highest values for R^2, indicating a strong correlation of the measured score values with the regression model, were found for the quality scores for the mental foramen (R^2=0.71-0.8) and linear movements (horizontal and vertical), as well as for angular movements in the vertical axis (yaw).

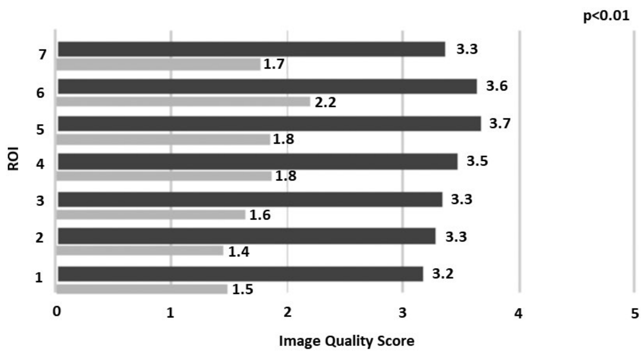

Fig. 6. Summarized image quality scores for ROIs 1-7 (P<0.01) (ROI 1: mental foramen; ROI 2: structure of mental trabecular bone; ROI 3: mandibular canal; ROI 4: pulp-dentin border of maxillary central front teeth, ROI 5: periodontal space of maxillary central front teeth; ROI 6: hard palate; ROI 7: nasal septum). The light gray column displays the mean image quality if no motion was detected, and the dark gray column displays the mean image quality if relevant motion was detected. ROI: region of interest.

Table 3 presents a summary of the results of the linear regression analysis of the extent of motion in different DOFs with image quality scores.

Discussion

Motion artifacts, which are common in CBCT imaging, represent a major reason for the impairment of image quality.[8,9,18,23,25,26] In dento-maxillofacial investigations, head movement is an especially important contributor to the occurrence of motion artifacts.[11,12,22]

The position of the patient during acquisition has a potential impact on the occurrence of motion-induced artifacts and subsequently on image quality. CBCT scans in a lying position have smaller head rotation angles than

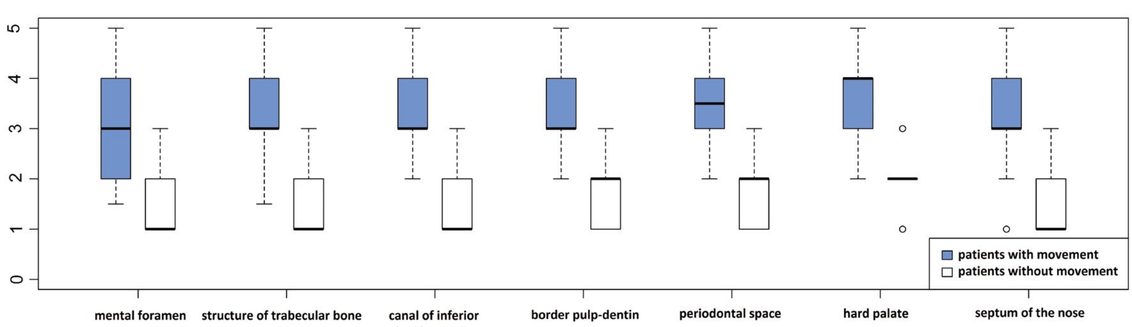

Fig. 7. Box plots depicting the mean values of image quality scores (Y-axis) for each of the 7 regions of interest.

Table 3. Results of the regression analysis of head movement and image quality scores (selection of anatomical regions of interest with highest accordance between movement and score values for each dimension of freedom)

Movement	Region of interest	B	ß	df	T	R^2	P value
Linear movement							
Horizontal	Mental foramen	15.86	0.28	1	3.25	0.80	<0.05
Vertical	Mental foramen	13.89	0.27	1	3.10	0.71	<0.05
Anterior-posterior	Trabecular bone	19.41	0.41	1	4.99	0.17	<0.05
Angular movement							
Pitch	Trabecular bone	224.81	0.47	1	5.95	0.22	<0.05
Yaw	Mental foramen	80.66	0.28	1	3.29	0.80	<0.05
Roll	Hard palate	201.68	0.39	1	4.75	0.15	<0.05

those in the sitting and standing positions.[17] However, dento-maxillofacial practitioners often favor image acquisition in the standing position because of the optimal space requirements of these CBCT devices.[2]

The literature focusing on head movements and subsequent artifacts in dento-maxillofacial imaging is still limited and has often based on *in vitro* investigations, while *in vivo* studies have mainly focused on different methodological aspects of motion detection.

In this prospective study, the authors investigate the occurrence rate of typical head movements and their influence on image quality during CBCT imaging in the standing position.

In the analysis presented herein, rotational head movements exceeding the preliminarily defined cut-off were the predominant locomotory pattern, found in 22% of the investigated patients. These data are supported by the results of Bontempi et al., who described a 32% higher likelihood of observing relevant rotation angles in terms of significant head motion in standing or sitting patients.[17] In our analysis, relevant translational head movement occurred in 6% of the patients during CBCT acquisition.

Any movement during CBCT acquisition leads to a geometrical error in the subsequent reconstruction process, resulting in reduced spatial resolution.[18] As the scan time becomes longer, the risk of potential motion artifacts increases.[24] Furthermore, as highlighted by Schulze et al., technical adjustments also need to be considered. In their study, the investigators demonstrated that motion artifacts were more likely to appear at higher nominal resolutions, again, mainly as a result of longer scan times.[11] Several studies have evaluated the frequency of motion in patients receiving CBCT imaging (Table 4).

Depending on the particular detection method, previous authors reported that movement occurred in between 13 and 83% of patients.[13,23,27,28] Although some movement was recorded in every patient in the present study, motion above the cut-off values for relevant movement was found in 24%. This proportion is in line with the findings mentioned above, especially considering differences among studies in the method of motion tracking and varying thresholds for defining relevant motion.

Movement during CBCT acquisition often results in double contours and the general impression of a blurred

Table 4. Summary of *in vivo* studies on the occurrence of motion and motion artifacts in CBCT imaging (NA: data not available)

Authors	Number of patients	Age	Conclusions
Bontempi et al. 2008[17]	63	NA	Head motion dependent on patient positioning Lying position presents lowest rates of motion and resulting artefacts
Donaldson et al. 2013[22]	200	NA	Motion especially likely in patients <16 years and >65 years Rate of artifacts: 4.5%
Hanzelka et al. 2013[21]	40	Mean 24 years	Motion especially at the beginning of the scan caused by noise and vibration of the device Dry-run scan to reduce patient's surprise
Nardi et al. 2014[29]	500	6-81 years	Motion dependent on age, scan time and anatomic subunit Rate of artifacts: 1.9%
Spin-Neto et al. 2014[28]	100	10-86 years (mean 34)	Rate of motion: 20% Detection of motion with high specificity and medium high sensitivity
Spin-Neto et al. 2015[23]	248 examinations in 190 patients	9-84 years (mean 32)	Rate of motion: 21% Image quality dependent on age, size of field of view (FOV), mechanical factors (cotton roll, head stabilization) Re-exposure rate: 6.4%
Schulze et al. 2015[27]	79 data sets	NA	Rate of motion: 13% Detection of motion: ROC analysis, AUC: 0.85
Spin-Neto et al. 2018[13]	162 examinations in 134 patients	9-73 years (mean 27)	Rate of motion: 82.7% (multiplanar: 45.7%) Movement ≥ 3 mm significantly impaired image quality and interpretability ($P<0.05$)

CBCT: cone-beam computed tomography, ROC: receiver operating characteristic, AUC: area under the curve image.[11] This study sought to confirm this finding by evaluating 7 different ROIs of the midface. Thereby, we deliberately avoided CBCT software post-processing of the raw image data by exporting them into Digital Imaging and Communications in Medicine datasets for objective examinations under standardized conditions. By scoring each ROI in every single patient, rather than focusing on the specific area of interest that may have been the main reason for obtaining the specific image, comparable data were generated for the whole cohort of 412 patients, thereby enhancing the validity of the conclusions.

The regression analysis showed that different types of motion affected image quality in different ROIs and that some regions were more susceptible to impairments of image quality (Tables 2 and 3). Specifically, movement along the horizontal and vertical axes (linear and angular) had more impact on image quality than movement along the anterior-posterior axis.

The strongest influence on image quality was demonstrated for linear and angular motion in the mental foramen. This may be attributable to the fact that even slight artifacts in small, punctate areas are more obvious and therefore are likely to result in worse score values. The image scores of the nasal septum were least influenced by movement in our analysis.

In most cases of imaging of the cranio-maxillofacial region, minor movements (e.g. respiratory movement, swallowing, movement of the tongue, muscle tremor of the lower jaw) during CBCT imaging can be tolerated, depending on the indication and anatomical region of interest. However, in high-definition CBCT scans, such as those used in endodontic examinations, even minimal motions may appreciably impair the image quality, as shown by our finding that movements affected the interpretability of punctate ROIs more strongly than they affected the interpretability of larger objects.[26] As a result, the examinations may need to be repeated, leading to an elevated exposure to radiation, or the practitioner may be forced to make a treatment decision based on insufficient or even uninterpretable images.[23] Several publications have reported that the possible impairment of image quality by motion artifacts may result in uninterpretable CBCT images (Table 4). Again, the definition of motion and image quality vary among different publications. Nonetheless, a consensus exists regarding the adverse effects of patient movement on image quality and interpretability, and again, our data support those findings.

A possible solution to this problem is to minimize motion artifacts by preventing head movements during CBCT acquisition. Nardi et al.[29] studied 3 different types of head rests and reported good overall comfort and a relevant reduction of movement in older patients. Still, patient motion led to repeated examinations in several cases.

The further reduction of scan time is another way to reduce the likelihood of patient movement, thereby avoiding motion artifacts. This strategy, however, is limited by the specific devices used for investigations and the indication and extent of the imaging procedure.

Fassi et al.[30] described a way to reduce motion-induced artifacts by the synchronization of CBCT acquisition and optical surface tracking of respiratory movements. Moreover, a marker-based numerical optimization method has been described to detect and prevent head motion.[20] The real-time detection of head movements and their subsequent incorporation into image post-processing via motion-artifact correction systems has been shown to be a feasible option to improve image quality.[9,26]

There are some limitations of this study that should be pointed out. Several authors have reported age- and general health-dependent occurrence rates of head motion during CBCT acquisition (Table 4).[8,22,31] These observations are highly logical and relevant. Nevertheless, in our analysis, patient age in general did not influence the quality of the CBCT scans, which may be explained by the low mean age of our cohort and the exclusion of patients under the age of 18.

A large proportion of the patients in our study received large field-of-view CBCT as preoperative imaging before orthognathic surgery. Therefore, the variability in terms of patients and general diseases was minimized, enhancing the homogeneity of our cohort. Furthermore, we could not demonstrate any significant correlations between image quality and general and/or neurological diseases. This is contradictory to the published data and might be attributable to the small number of patients with neurological diseases evaluated in the present study.[23] Here, further investigations including more patients are necessary to validate the observations presented in this study. Another relevant point is the variety of different CBCT devices used in oral and maxillofacial departments, as different devices may provide other head rests and stabilizers to prevent head movements. As a consequence, the results reported in this study may not be generalizable, as the occurrence of head movements and, consequently, of artifacts is strongly dependent on the hardware used in each investigation.

Finally, other potential sources of artifacts resulting in reduced image quality were not examined in this investigation. Technical causes of artifacts, such as electrical and phantom noise, scatter, beam hardening, and the exponential edge-gradient effect, as well as artifacts caused by the materials used for dental restorations, are known problems that must be taken into account.[11,32-34]

This study presents an analysis of the direct correlation of different patterns of patient motion on image quality in CBCT scans of the oral and maxillofacial region in a large cohort of patients, and the results of similar studies could be validated. Although significant technical advances have been made in recent years in implementing motion artifact correction tools, other studies are warranted to further reduce the need for re-exposure and to improve interpretability, thereby possibly enhancing operational areas for CBCT imaging.

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Conflicts of interest: None

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