RESEARCH ARTICLE

An *ex vivo* study of automated motion artefact correction and the impact on cone beam CT image quality and interpretability

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Objectives: To assess the impact of head motion artefacts and an automated artefact-correction system on cone beam CT (CBCT) image quality and interpretability for simulated diagnostic tasks.

Methods: A partially dentate human skull was mounted on a robot simulating four types of head movement (anteroposterior translation, nodding, lateral rotation, and tremor), at three distances (0.75, 1.5, and 3 mm) based on two movement patterns (skull returning/not returning to the initial position). Two diagnostic tasks were simulated: dental implant planning and detection of a periapical lesion. Three CBCT units were used to examine the skull during the movements and no-motion (control): Cranex 3Dx (CRA), Orthophos SL 3D (ORT), and X1 without (X1_{wo}) and with (X1_{wi}) an automated motion artefact-correction system. For each diagnostic task, 88 examinations were performed. Three observers, blinded to unit and movement, scored image quality: presence of stripe artefacts (present/absent), overall unsharpness (present/absent), and image interpretability (interpretable/non-interpretable). κ statistics assessed interobserver agreement, and descriptive statistics summarized the findings.

Results: Interobserver agreement for image interpretability was good (average $\kappa = 0.68$). Regarding dental implant planning, X1_{wi} images were interpretable by all observers, while for the other units mainly the cases with tremor were non-interpretable. Regarding detection of a periapical lesion, besides tremor, most of the 3 mm movements based on the “not returning” pattern were also non-interpretable for CRA, ORT, and X1_{wo}. For X1_{wi}, two observers scored 1.5 mm tremor and one observer scored 3 mm tremor as non-interpretable.

Conclusions: The automated motion artefact-correction system significantly enhanced CBCT image quality and interpretability.

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Keywords: patient movement; motion artefacts; cone beam CT; image quality.

Introduction

Patient head movement during the acquisition of cone beam CT (CBCT) images of the dentomaxillofacial region is a well-documented challenge.^{1–3} The long acquisition time for CBCT, ranging from five to 40 s⁴ impedes the patient's ability to keep still during examination, particularly children.^{1–3} Further, other reasons for patient movements, such as systemic diseases in elderly patients (*e.g.* Parkinson's disease), must be

considered.³ Independent of their origin, movements are likely to produce image artefacts, so-called patient motion artefacts.^{1–3}

Recent *ex vivo* and *in vivo* studies have established a causal relationship between patient movement and the presence of artefacts in the images.^{5–9} The findings suggest that the occurrence of motion artefacts will depend on certain characteristics of the movement, such as duration, distance, and type (associated with motion complexity).^{3,8–10} If the artefacts are severe, leading to significant loss in image quality, the CBCT image

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sections may not be interpretable.³ Recent *in vivo* studies showed that movements ≥ 0.5 mm take place in nearly 80% of CBCT examinations¹¹ and suggested that the presence of patient movement ≥ 3 mm had a significant impact on CBCT image quality and interpretability.¹² In this case, there is a need to repeat the examination, multiplying the radiation dose to the patient.³

To overcome the drawbacks of patient motion, the literature has suggested that CBCT reconstruction algorithms should consider patient motion, *i.e.* provide automated correction of motion artefacts.^{3,11,13} However, if information on patient movement is to be used in motion artefact correction processes, accurate movement tracking methods are needed.¹³ A previous study presented an objective method to register patient movement three-dimensionally, based on an accelerometer/gyroscope system,¹¹ but the accuracy of the method could not be determined, because there was no reference standard for true motion. The same group of researchers, therefore, suggested a second objective method to track patient head movements, based on the use of three cameras, which track the position of a dot pattern mounted on a headband worn by the patient during the CBCT examination.¹³ This method was assessed in an *in vitro* robot study and demonstrated to correctly detect small (*i.e.* 0.25 mm) movements with a measurement error no larger than 55 μ m, which is below the available CBCT voxel size.¹³ So far, no further information on how the head tracker method may be used for subsequent motion artefact correction has been presented.

Thus, the objective of the present qualitative *ex vivo* study (*i.e.* using a dry skull embedded in wax) was to assess the impact of head motion artefacts, and of an automated motion artefact-correction system based on

a 3D head tracking method and iterative reconstruction algorithm, on CBCT image quality and interpretability for simulated mandibular implant planning and peri-apical lesion detection.

Methods and materials

Experimental setup—robot programming

A partially dentate human skull embedded in wax to simulate soft tissues¹⁴ was mounted on a robot (UR10, Universal Robots, Odense, Denmark) as depicted in Figure 1. The robot contains six rotating joints (*i.e.* rotary actuators) that allow precise control of angular position, velocity, and acceleration. The robot may be programmed to simulate any patient movement in all freely selected axes, at a freely selected speed, using freely selected excursion angles. According to the manufacturer, the robot is able to perform movements with a precision of 0.1 mm for translational and rotational movements. Using a wired control panel connected to the robot, the preprogrammed movement is started, and the program automatically stops when the movement has been performed. In our study, all joints were controlled with respect to time, speed, and path by the control panel.

The robot was programmed to reproduce four head movement types, which were selected on the basis of clinical evidence, *i.e.* movements previously observed to be performed by patients during CBCT examination.^{11,12} The four types of simulated head movement were anteroposterior translation, nodding, lateral rotation, and tremor. As all movements are based on the rotation of the robot joints, rotation angles were adjusted to correspond to movement distances of 0.75,

Figure 1 Experimental setup. (a) The partially dentate human skull embedded in wax integrated with the robot. The arrow points at the dotted plate attached to the unit, but isolated from the skull. (b) The skull is equipped with a headband containing the plastic, dotted plate that is tracked by three dedicated optical cameras. (c) Detail of the three dedicated optical cameras, while capturing images of the dotted plate during the full examination to determine the orientation and position of the skull.

1.5, and 3 mm, when measured at the skull's anterior nasal spine. These distances were selected based on what was previously observed in a sample of patients, in whom head movements were registered using an accelerometer/gyroscope system,¹¹ and to include movement distances, which have been found to often lead to non-interpretable images.¹² Movements were set to occur at a speed of 5 mm s⁻¹ to mimic fast head movements, which lasted no more than 0.5 s, and started when the tube was exactly at the midpoint of its rotation around the skull. All movements but tremor were programmed to reflect two movement patterns: one in which, after reaching the maximum excursion for the programmed movement, the skull returned to the start position, and a second pattern in which the skull did not return to the start position, *i.e.* the movement ended at the maximum excursion of the robot joint for the programmed movement. A programme code, in which the joints of the robot were not activated and the skull was kept stationary, was used to provide a “no-motion” (control) situation.

Image acquisition and simulation of clinical tasks

Three CBCT units were selected to examine the skull during the head movements and with no-motion: Cranex 3Dx (CRA, Soredex Oy, Finland), Orthophos SL 3D (ORT, Sirona Dental Systems GmbH, Germany), and X1 (3Shape, Denmark), the latter without (X1_{wo}) and with (X1_{wi}) the automated motion artefact-correction system. Image acquisition parameters are presented in Table 1.

Two diagnostic tasks with clinical relevance within dentomaxillofacial radiology were simulated. One was the planning of dental implants in the premolar region of the mandible, which mostly focus on the identification of the contours of the bone tissue, and the other was the diagnosis of a periapical lesion related to a root-filled mandibular canine, which also involves the identification of dental-tissue contours and image contrast variation. In total, 88 examinations were performed for each diagnostic task (four movement types, in three movement distances, and in two movement patterns).

Correction of motion artefacts

The motion artefact-correction system of the X1 CBCT unit is based on a two-step procedure. Step one is the

tracking of the skull-robot movements using the head tracker apparatus integrated with the unit. The second step is an iterative reconstruction of the acquired projection images incorporating the head tracker data.

Briefly, and as previously described,¹³ the 3D head tracking apparatus consists of three optical cameras (3Shape, Copenhagen, Denmark) integrated in the unit's gantry carrying the X-ray tube and sensor. The three cameras are mounted on a ring with 55 mm radius with 120° angular separation and with a 20° inclination towards the centre of the camera ring. The cameras operate at 15 frames-per-second (adjusted to 45 for the TRM movements) and track the position of a dotted plate (5 cm in diameter, containing dots 2 mm in diameter and with a 1 mm distance between each other) mounted on a headband placed around the skull, as shown in Figure 1b,c. In all captured images from the three cameras, the dots are identified by a dedicated image processing algorithm (3Shape, Copenhagen, Denmark), which detects the dots printed on the plate. Subsequently, the same algorithm determines the 3D orientation and position of the dots, consequently tracking the position of the skull relative to the X-ray tube and sensor in three dimensions. During a CBCT acquisition, each of the acquired X-ray projections is, thus associated with a matrix describing the exact position and angulation of the X-ray tube and sensor in relation to the skull's position—precisely at the time of image capture.

The reconstruction of the X-ray projections is based on mathematical optimization, iteratively minimizing a dedicated cost function. This cost function describes how well a given 3D reconstruction matches the acquired projections by synthesizing a set of artificial X-ray projections from the current solution, and comparing the synthesized projections to the acquired projections. In each iteration, the 3D volume is adapted such that the difference between the simulated and acquired projections is reduced. Taking advantage of the inherent head tracking data, as each X-ray projection is synthesized at each iteration, the observed motion is taken into account. Consequently, the 3D reconstruction that minimizes the cost function is the voxel volume, in which all movements have been eliminated. The algorithm utilizes the graphics card of the reconstruction workstation to

Table 1 Image acquisition protocols (CRA: Soredex Oy, Finland; ORT: Sirona Dental Systems GmbH, Germany; X1: X1, 3Shape, Denmark)

Parameter	CBCT unit		
	CRA	ORT	X1
FOV	5.0 × 5.0 cm	5.0 × 5.5 cm	5.0 × 5.0 cm
kV	90	85	90
mA	6	10	10
Voxel resolution	0.125 mm	0.160 mm	0.150 mm
DAP	340 mGy·cm ²	214 mGy·cm ²	214 mGy·cm ²

CBCT, cone beam CT; CRA, Cranex 3Dx; DAP, Dose–area product; FOV, field of view; ORT, Orthophos SL 3D. The X1 was used with (X1_{wi}) and without (X1_{wo}) automated motion artefact correction.

achieve fast reconstructions, performing this task in approximately three minutes, considering the field of view (FOV) and the resolution of the images acquired in the present study.

The motion artefact-correction system serves an additional purpose: any imperfection in the mechanical movement of parts in the CBCT unit is also captured and compensated for in the data reconstruction. Conceptually, there is no difference between correcting head movements and imperfections in the mechanical implementation. It is thus no longer a limiting factor if, *e.g.* the rotational movements of the unit during data acquisition are not perfectly reproducing the desired nominal motor trajectories. To test whether image quality would be hampered if the motion artefact-correction system was not activated, images without such correction were also acquired ($X1_{wo}$). To acquire these images, a dotted plate was attached to the unit and isolated from the skull, as presented in Figure 1a. In this way, the dotted plate was fully independent of the robot and of the skull.

Image quality and interpretability

The original data sets and their relation with the performed movement were saved, and the data sets were coded to blind the observers. The acquired DICOM sets were imported into reconstruction software (OnDemand 3D; Cybermed, Seoul, Republic of Korea), and each one was adjusted to present optimal image characteristics, *i.e.* windowing (values for the centre level and bandwidth of the displayed shades of grey) of the image sets was adjusted. The principal investigator (RS-N, not part of scoring the images) collected three representative image sections of each acquired volume, in the axial, sagittal, and coronal plane. The image sections were selected to show the same anatomic area (*i.e.* region of interest), based on the same sectioning plane and augmentation. Subsequently, these image sections were organized together in coded “panels”.

Three independent observers working with CBCT for several years were informed of the indication of the CBCT examination (diagnostic task: planning of dental implants or diagnosis of a periapical lesion), but were not informed about the true state of movement and imaging modality (*i.e.* CBCT unit). Observers were not aware of the prevalence of movement and movement types, distances, and patterns in the sample. Image panels were assessed on a 24-inch flat screen monitor (Dell P2412H, Dell Inc., Round Rock, TX) using dedicated software to visualize the images (ImageJ, NIH) in a room with dimmed light. Image quality was scored in terms of the presence of stripe/streak artefacts related to movement (present/absent), overall unsharpness (present/absent), and image interpretability (interpretable/not interpretable). Regarding the diagnosis of a periapical lesion, observers further scored the presence of stripe artefacts related to radiopaque material (root filling) in the FOV.

To avoid observer fatigue, scoring sessions were limited to 1 hour in a day.

Data treatment

Commercially available software (IBM Corp., New York, NY; formerly SPSS Inc., Chicago, IL) was used for data evaluation. Interobserver agreement was assessed by means of κ statistics. Descriptive statistics summarized the findings for all observers individually. Cross-tables illustrated the relationship between presence of movement stripes/presence of overall unsharpness/not interpretable images and the CBCT unit/movement characteristics (*i.e.* movement type, distance, and pattern).

Results

Interobserver agreement for the presence of stripe artefacts related to movement was moderate (0.57 on average). For stripes related to radiopaque material in the FOV, agreement was fair (0.39 on average). Regarding the presence of overall unsharpness, interobserver agreement was good (0.67 on average). Interobserver agreement was good (0.68 on average) concerning the interpretability of the images.

Regarding the planning of dental implants, for CRA the presence of movement stripes was scored in 81.8% (68.2–90.9), for ORT in 80.3% (54.5–95.5), for $X1_{wo}$ in 54.5% (13.6–95.5), and for $X1_{wi}$ in 7.6% (0–13.6) of the cases. For $X1_{wo}$, two observers scored images with no movement as having movement stripes. Presence of unsharpness was scored in 83.4% (72.7–95.5) of CRA and in 83.3% (63.6–95.5) of ORT images, while for $X1_{wo}$ unsharpness was present in 71.2% (50.0–95.5) and for $X1_{wi}$ in 21.2% (13.6–27.3) of the cases. For $X1_{wo}$, all observers scored images with no movement as presenting overall unsharpness, while one observer also scored the presence of overall unsharpness in CRA and $X1_{wi}$ control images. When the automated motion artefact-correction system was used ($X1_{wi}$), the presence of stripes and unsharpness in the images was mainly connected with tremor movements. Regarding the interpretability of the images, using the motion artefact-correction system ($X1_{wi}$) caused all images to be scored as interpretable by all observers, while for all other tested units the cases with tremor movements were mainly scored as non-interpretable. All observers' scores regarding the planning of dental implants are presented in Table 2, while Figure 2 presents examples of the images.

Regarding the diagnosis of a periapical lesion, presence of metal artefacts was scored in 66.6% (54.5–72.7) of the images acquired with CRA, 62.1% (40.9–100) of the images acquired with ORT, 62.1% (45.5–86.4) of the $X1_{wo}$ images, and 15.1% (9.1–22.7) of the $X1_{wi}$ images. For CRA, movement stripes were scored in 84.9% (68.2–90.9), for ORT in 80.3% (54.5–95.5), for $X1_{wo}$ in

Table 2 Three observers' scores regarding the presence of movement stripes (filled circle, present; empty circle, absent), overall unsharpness (filled circle, present; empty circle, absent), and image interpretability (filled circle, non-interpretability; empty circle, interpretability), according to movement pattern, type, and distance, regarding dental implant planning

Pattern	Type	Distance (mm)	Movement stripes					Unsharpness					Non-interpretability image				
			CRA	ORT	XI _{no}	XI _{ref}	CRA	ORT	XI _{no}	XI _{ref}	CRA	ORT	XI _{no}	XI _{ref}	CRA	ORT	XI _{ref}
Returning to initial position	Anteroposterior translation	0.75	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●
		1.50	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●
		3.00	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●
	Nodding	0.75	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●
		1.50	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●
		3.00	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●
	Lateral rotation	0.75	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●
		1.50	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●
		3.00	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●
	Tremor	0.75	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●
		1.50	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●
		3.00	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●
Not returning to initial position	Anteroposterior translation	0.75	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○
		1.50	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●
		3.00	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●
	Nodding	0.75	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●
		1.50	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●
		3.00	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●
	Lateral rotation	0.75	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○
		1.50	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●
		3.00	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●
Control (no-motion)	Lateral rotation	0.75	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○
		1.50	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○
		3.00	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○	○●○

CRA, Cranex 3Dx; ORT, Orthophos SL 3D; X1_{no}, X1 with; X1_{ref}, X1 without.

Figure 2 Representative axial, sagittal, and cross-sectional images regarding implant planning, and considering the four CBCT image-acquisition setups (CRA, ORT, X1wo, and X1wi). The first four rows show control images with no movement. The four rows in the middle show images acquired with a 3 mm nodding movement. The last four rows show images acquired with a 3 mm tremor movement. CBCT, cone beam CT; CRA, Cranex 3Dx; ORT, Orthophos SL 3D; X1_{wo}, X1 without; X1_{wi}, X1 with.

54.5% (13.6–95.5), and for X1_{wi} in 7.6% (0–13.6) of the cases. For ORT, two observers scored images with no movement as having movement stripes. Unsharpness was scored in 90.9% (86.4–95.5) of CRA and in 96.9% (90.9–100) of ORT images, while for X1_{wo} unsharpness was present in 83.4% (72.7–95.5) and for X1_{wi} in 15.1% (13.6–18.2) of the cases. All observers scored X1_{wo} images with no movement as presenting overall unsharpness, while two observers also scored ORT control images in the same manner. When the automated motion artefact-correction system (X1_{wi}) was used, the presence of stripes and unsharpness in the images was connected solely with tremor movements. Concerning the interpretability of the images, non-interpretable images were mostly those in which tremor movements were present. For CRA, ORT, and X1_{wo}, some cases, in which large movements were based on the “not returning” movement pattern, were also scored as non-interpretable by some observers. When automated motion artefact correction (X1_{wi}) was used, images with medium (1.5 mm) tremor movements were scored as non-interpretable by two observers, while one observer also scored the image with large (3.0 mm) tremor movements in the same manner. The scores regarding AP are presented in Table 3, while Figure 3 presents examples of the images.

Discussion

It has been reported that CBCT image artefacts are mostly connected with discrepancies between the mathematical approach (*i.e.* algorithms) used for 3D reconstruction and the actual physical conditions of the image acquisition setup, which are defined by the CBCT unit's settings together with the characteristics of the object/patient under examination.² Among the sources of alteration in the image acquisition setup, there is the fact that patients cannot remain perfectly still during the full examination time for different reasons, ranging from breathing and heart beats to unintentional movements, which deserves special attention.^{1,3} To the present, the image reconstruction algorithms do not consider patient movements during the volume reconstruction process, leading to artefacts in the final images.^{1–3}

According to the literature, there are three possible approaches to eliminate (or minimize) patient motion artefacts in CBCT images.¹⁵ The first is shortening the scanning time, giving less opportunity for the patients to move.^{1,3,16} This solution is currently not feasible, due to the limited temporal resolution of the flat panel detectors used in the CBCT units.¹⁶ A second possibility is to use systematic patient positioning and stabilization devices allied with patient and operator instruction.^{3,17} On that direction, the hardware solutions available to immobilize the patient's head in a steady position during image acquisition, such as chin rests, bite pieces, and head restraints, have their limits, and might not eliminate all movements.^{1,3} However, studies evaluating the

Table 3 Three observers' scores regarding the presence of movement stripes (filled circle, present; empty circle, absent), overall unsharpness (filled circle, present; empty circle, absent), and image interpretability (filled circle, present; empty circle, absent), according to movement pattern, type, and distance, regarding detection of a periapical lesion

<i>Pattern</i>	<i>Type</i>	<i>Distance (mm)</i>	<i>Movement stripes</i>				<i>Unsharpness</i>				<i>Non-interpretability image</i>			
			<i>CRA</i>	<i>ORT</i>	<i>XI_{no}</i>	<i>XI_{ref}</i>	<i>CRA</i>	<i>ORT</i>	<i>XI_{no}</i>	<i>XI_{ref}</i>	<i>CRA</i>	<i>ORT</i>	<i>XI_{no}</i>	<i>XI_{ref}</i>
Returning to initial position	Anteroposterior translation	0.75	● ○ ●	● ● ●	● ● ●	○ ○ ○	● ○ ○	● ● ●	● ● ●	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○
		1.50	● ● ●	● ● ●	● ● ●	○ ○ ○	● ● ●	● ● ●	● ● ●	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○
		3.00	● ● ●	● ● ●	● ● ●	○ ○ ○	● ● ●	● ● ●	● ● ●	○ ○ ○	○ ○ ○	● ○ ○	○ ○ ○	○ ○ ○
		0.75	● ○ ●	● ○ ●	○ ○ ○	○ ○ ○	● ● ●	● ● ●	● ● ●	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○
	Nodding	1.50	● ● ●	● ○ ●	○ ○ ○	○ ○ ○	● ● ●	● ● ●	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○
		3.00	● ● ●	● ○ ●	○ ○ ○	○ ○ ○	● ● ●	● ● ●	● ● ●	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○
	Lateral rotation	0.75	● ● ●	● ● ●	● ● ●	○ ○ ○	● ● ●	● ● ●	● ● ●	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○
		1.50	● ● ●	● ● ●	● ● ●	○ ○ ○	● ● ●	● ● ●	● ● ●	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○
	Tremor	3.00	● ● ●	● ● ●	● ● ●	○ ○ ○	● ● ●	● ● ●	● ● ●	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○
		0.75	● ● ●	● ● ●	● ● ●	○ ○ ○	● ● ●	● ● ●	● ● ●	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○
	Anteroposterior translation	1.50	● ● ●	● ● ●	● ● ●	○ ○ ○	● ● ●	● ● ●	● ● ●	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○
		3.00	● ● ●	● ● ●	● ● ●	○ ○ ○	● ● ●	● ● ●	● ● ●	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○
Not returning to initial position	Anteroposterior translation	0.75	● ● ●	● ● ●	● ● ●	○ ○ ○	● ● ●	● ● ●	● ● ●	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○
		1.50	● ○ ●	● ○ ●	● ● ●	○ ○ ○	● ○ ●	● ● ●	● ● ●	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○
		3.00	● ○ ●	● ● ●	● ● ●	○ ○ ○	● ● ●	● ● ●	● ● ●	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○
		0.75	● ● ●	● ● ●	● ● ●	○ ○ ○	● ● ●	● ● ●	● ● ●	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○
	Nodding	1.50	● ○ ○	● ● ●	● ● ●	○ ○ ○	● ● ●	● ● ●	● ● ●	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○
		3.00	● ● ●	● ● ●	● ● ●	○ ○ ○	● ● ●	● ● ●	● ● ●	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○
	Lateral rotation	0.75	● ● ●	● ● ●	● ● ●	○ ○ ○	● ● ●	● ● ●	● ● ●	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○
		1.50	● ● ●	● ● ●	● ● ●	○ ○ ○	● ● ●	● ● ●	● ● ●	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○
	3.00	0.75	○ ○ ○	● ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○
		1.50	○ ○ ○	● ● ●	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○
	Control (no-motion)	3.00	○ ○ ○	● ● ●	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○
			○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○

CBCT, cone beam CT; CRA, Cranex 3Dx; DAP, dose-area product; FOV, field of view; ORT, Orthophos SL 3D; X1_{ref}, X1 with; X1_{no}, X1 without.

Figure 3 Representative axial, sagittal, and cross-sectional images regarding diagnosis of apical periodontitis, and considering the four CBCT image-acquisition setups (CRA, ORT, X1wo, and X1wi). The first four rows show control images with no movement. The four rows in the middle show images acquired with a 3 mm nodding movement. The last four rows show images acquired with a 3 mm tremor movement. CBCT, cone beam CT; CRA, Cranex 3Dx; ORT, Orthophos SL 3D; X1_{wi}, X1 with; X1_{wo}, X1 without.

impact of these patient fixation devices are still missing. The third approach is to use software-based, automated motion artefact correction.³ This approach has shown good results for thoracic and abdominal areas¹⁸ and has also been mentioned for imaging of the head and neck region.¹⁹ This is, however, the first study to qualitatively assess the impact of automated motion artefact correction on CBCT image quality and interpretability for common dentomaxillofacial tasks.

Various approaches to correct CBCT data sets for motion have been suggested.¹⁹ An important step refers to the accuracy of the method used to detect and quantify (*i.e.* track) patient movement. One possibility is to rely solely on the raw image projections generated during an examination, tracking patient movement based on optical flow measurements.^{6,19} This method, however, might not be accurate enough to detect small-distance movements which take place perpendicular to the CBCT detector.⁶ Further, as optical flow measurements are directly related to brightness variation in the images, it may be affected by the innate voxel value variation present in CBCT data sets, leading to inaccuracy in patient movement tracking.^{20–24}

The use of movement tracking sensors and fiducial markers placed on the patient is another possibility.¹⁹ A recent study suggested to use accelerometers and gyroscopes to track patient head movements.¹¹ Such systems, however, might have their precision affected by their innate inaccuracy, which induces errors in the measured angular and spatial positions.²⁵ When used to track patient movements, the accelerometer-gyroscope method presented an innate error of approximately 0.5 mm.¹¹ As for the fiducial markers, these could be tracked directly on the CBCT image projections (*i.e.* radiopaque markers present in the FOV), or optically, using dedicated cameras focused at the fiducials during the course of an examination.^{13,19,26} The obvious risk of introducing metal-related artefacts to the final reconstructed images could be one of the major drawbacks of the method.²⁷ Artefacts would interfere with both the image quality and the accuracy of the tracking method.¹⁹ Thus, the use of optically tracked fiducials, as in the artefact-correction system used in the present study, may be preferable. The measurement error of this tracking method is below the CBCT voxel size.¹³

No matter the source providing information on patient movement, motion tracking data must also be accurately synchronized with projection data acquisition, and proper calibration is needed to convert tracker coordinates to image coordinates.²⁸ In the present study, no direct measurements to test the data synchronization of the motion artefact-correction system was performed. On the other hand, an image quality and interpretability assessment protocol was used to assess if the correction system performed adequately. Two diagnostic tasks were selected, relevant for dentomaxillofacial radiology: implant planning and periapical lesion detection.²⁹ Certain movement characteristics were selected

to reflect those previously shown in clinical studies to be associated with a large prevalence of image artefacts and non-interpretable images.¹² During scoring, CBCT images were assessed in a “static” manner, from a panel including the axial, the sagittal, and the coronal views of the region of interest. This could be mentioned as one of the possible sources for the large range among the observers regarding stripe artefacts. One could speculate that variability would be smaller if the volumes were assessed in a dynamic manner, in which the observers could freely navigate the volume. But in that case, it would be impossible to blind the observers towards unit, since the FOVs, among other characteristics, are different among the CBCT units.

The present results showed that the prevalence of stripe artefacts and overall unsharpness in the images acquired during skull motion was high. For the diagnosis of a periapical lesion, the observers also acknowledged the presence of beam-hardening artefacts connected with the root-filling material. When the automated motion artefact-correction system was used, the presence of stripes and unsharpness in the images was mainly connected with tremor movements. This also led the prevalence of non-interpretable images to be much lower when the motion artefact-correction system was used.

Not all large movements led to non-interpretable images, even when no motion artefact correction was used, and this fact ratifies what has previously been reported. A study assessing CBCT images of young patients, who moved during examination and who had no metal in the FOV, concluded that not only the type (*i.e.* complexity) and the distance of the movement, but also the number of times the patient moved, was associated with image quality.⁷ The same study showed that the patients often moved more than once during the examination (average of three movements during an examination of 20 s), and that most movements lasted longer than a second (2 s, on average).⁷ The main drawback of that study is that no true tracking of patient movement was performed, since movement was defined solely based on subjective video observation of the patient. To define which movements to be tested in the present study, a recent study, based on a more objective patient-tracking method (accelerometer/gyroscope), found that large (larger than 3 mm) and complex (*i.e.* multiplanar) movements, such as tremor and nodding, were more prone to cause an image quality loss, leading to non-interpretable images.¹² In the cited study, a drawback was that only the “worst” movement (*i.e.* largest distance) was considered, rather than the several, isolated movements,

which could have taken place during the examination. We believe that movement characteristics, which will definitely hamper the diagnostic outcome of a CBCT examination and therefore lead to re-exposure, have yet to be explored in detailed diagnostic accuracy studies.³ Further, this should include new movement tracking methods.¹³

When the motion artefact-correction system was not activated (X1_{wo} unit), some images with no movement were scored with movement stripes and overall unsharpness. However, the setup used to “inactivate” the motion artefact-correction system is not suggested by the producer. This could be influenced by factors such as unit vibration, which would cause the dotted plate to move, influencing the image reconstruction process.

The results of the present study suggest the appropriateness of a motion artefact-correction system. Further studies on motion artefact-correction in daily clinical practice are needed to measure the impact of the method, *e.g.* following a quality assurance audit cycle. Current European guidelines suggest that the “assessment of the clinical quality of images should be a part of a quality-assurance program for CBCT,” guarantying that no more than 5% of CBCT examinations should be classified as non-interpretable, and therefore, repeated.²⁹ According to these guidelines, in each successive quality assurance audit cycle, the goal is to reduce the proportion of non-interpretable examinations by 50%,²⁹ which could be used as a threshold to determine the actual impact of using a motion artefact-correction system as a routine in the clinic.

Conclusion

The automated motion artefact-correction system significantly enhanced CBCT image quality and interpretability considering two maxillofacial-related diagnostic tasks.

Conflict of interest

Thomas S. Sørensen works for 3Shape (Copenhagen, Denmark), which is the company producing one of the CBCT units tested in the present study (X1). This coauthor provided the adequate setup of the equipment and the technical information on how the motion artefact-correction system works. He was not involved in designing the study or in the data treatment and evaluation of the results.

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