RESEARCH ARTICLE

Patient movement characteristics and the impact on CBCT image quality and interpretability

¹Rubens Spin-Neto, ²Cláudio Costa, ²Daniela MRA Salgado, ²Nataly RM Zambrana, ¹Erik Gotfredsen and ¹Ann Wenzel

¹Department of Dentistry and Oral Health, Aarhus University, Aarhus, Denmark; ²Department of Stomatology, School of Dentistry, University of São Paulo, São Paulo, Brazil

Objectives: To assess the impact of patient movement characteristics and metal/radiopaque materials in the field-of-view (FOV) on CBCT image quality and interpretability.

Methods: 162 CBCT examinations were performed in 134 consecutive (*i.e.* prospective data collection) patients (age average: 27.2 years; range: 9–73). An accelerometer-gyroscope system registered patient's head position during examination. The threshold for movement definition was set at ≥ 0.5 -mm movement distance based on accelerometer-gyroscope recording. Movement complexity was defined as uniplanar/multiplanar. Three observers scored independently: presence of stripe (*i.e.* streak) artefacts (absent/"enamel stripes"/"metal stripes"/"movement stripes"), overall unsharpness (absent/present) and image interpretability (interpretable/not interpretable). Kappa statistics assessed interobserver agreement. χ^2 tests analysed whether movement distance, movement complexity and metal/radiopaque material in the FOV affected image quality and image interpretability. Relevant risk factors ($p \leq 0.20$) were entered into a multivariate logistic regression analysis with "not interpretable" as the outcome.

Results: Interobserver agreement for image interpretability was good (average = 0.65). Movement distance and presence of metal/radiopaque materials significantly affected image quality and interpretability. There were 22–28 cases, in which the observers stated the image was not interpretable. Small movements (*i.e.* < 3 mm) did not significantly affect image interpretability. For movements ≥ 3 mm, the risk that a case was scored as "not interpretable" was significantly ($p \leq 0.05$) increased [OR 3.2–11.3; 95% CI (0.70–65.47)]. Metal/radiopaque material was also a significant ($p \leq 0.05$) risk factor (OR 3.61–5.05).

Conclusions: Patient movement ≥ 3 mm and metal/radiopaque material in the FOV significantly affected CBCT image quality and interpretability.

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

Introduction

In dentomaxillofacial CBCT imaging, patient head movements may occur, in spite of efforts to keep the patient still.^{1–3} Although these movements will likely produce artefacts,^{1–3} not many studies in the literature have focused on establishing a causal relationship between patient movement and the presence of artefacts

in the images. If the loss in image quality caused by artefacts is significant, there might be a need for repeating the examination, increasing the radiation dose to the patient.¹

It has been suggested that the occurrence of motion artefacts may depend on certain characteristics of the movement, such as distance and complexity.¹ However, *ex vivo*^{4–6} and *in vivo*^{7–10} studies on the topic are sparse, reporting a wide prevalence range of patient movement

Correspondence to: Dr Rubens Spin-Neto, E-mail: rsn@odont.au.dk

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and motion artefacts in CBCT examinations. Unfortunately, most of the *ex vivo* studies are limited by the fact that only few movement types were tested, not testing the exact effect of diverse movement characteristics on the final image features.^{4,5} Moreover, *in vivo* studies are based on movement detection methods, which are to a certain degree subjective, ranging from having no reference standard for movement detection,^{7,8} to patient video observation.¹⁰ A more objective method based on optical flow measurements has also been used for *in vivo* patient movement detection, but these measures may be affected by the innate voxel value variation present in CBCT datasets, also leading to inaccuracy in detecting the movements.⁹ The lack of a more objective patient tracking method makes it difficult to conduct studies focusing on the impact of patient movement characteristics on CBCT image quality and interpretability. Therefore, less subjective reference standards for movement are needed.

Following this demand, we have recently suggested a three-dimensional method for registering patient head movements based on an accelerometer-gyroscope (AG) tracking system.¹¹ In that previous study, it was also concluded that motion prevalence differed immensely between a subjective patient video observation method and the objective three-dimensional tracking system.¹¹ In the present study, the aim was to assess the impact of patient movement characteristics, as recorded by the AG tracking system, on CBCT image quality and interpretability. The impact of metal/radiopaque materials present in the field-of-view (FOV) was also assessed.

Methods and materials

Study population

The basic study population of this study consisted of 134 consecutive (*i.e.* prospective data collection) patients (109 female/53 male, age average: 27.2 years; range: 9–73), in whom 162 CBCT examinations were performed, at the Section of Oral Radiology, Department of Dentistry and Oral Health, Aarhus University, Denmark between November 2013 and November 2014. Patients agreed to be AG-tracked during the CBCT examination, and reported no history of systemic disorders, which could lead to impaired head movement control, such as Parkinson's disease. CBCT examinations were performed using a Scanora 3D unit (Soredex Oy, Tuusula, Finland, with 6 × 6 cm FOV, voxel size 0.13 mm, and scanning time 23 s). In this unit, patients were seated and a chin-rest used to stabilize the mandible and two vertical plastic bars (one in each side) to support the head. CBCT examination was requested for one of three diagnostic tasks: possible endodontic problem ("Endo", 35 examinations), resorption of teeth adjacent to an impacted upper canine ("IUC", 48 examinations) or resorption in the second molar/proximity to the mandibular canal in impacted lower third molars ("I3M", 79 examinations). In 48 examinations (approximately 30%

of the sample), metal or another radiopaque material (*e.g.* root-filling material) was present in the FOV (as assessed by Spin-Neto, prior to providing the images to the observers). Approval of the methodology by an Ethics Committee was not required, since the CBCT examination was requested by the patient's clinician and ratified by a radiologist, and the study did not interfere with image acquisition.

Accelerometer-gyroscope system registration

An AG system was used, which recorded the patient's head position during the examination in all planes.¹¹ Briefly, the system consisted of two iPod touch devices (Apple Inc., Cupertino, CA) with their AG synchronized *via* Bluetooth connection to track the movement on the *x*-, *y*- and *z*-axes in degrees, at a rate of 50 readings/s using dedicated software (Gyro-kun 3; Medical Informatics Lab., Kitasato University, Tokyo, Japan). One of the devices was attached to the patient's head using a plastic tiara, while the other was attached to the CBCT arm containing the RX tube.¹¹ AG recorded when the CBCT arm started and finished moving. AG data containing the synchronized position on the *x*-, *y*- and *z*-axes of both devices were saved as comma-separated value files, which could later be read by the statistical software package.

Patient movement definition

To define the threshold for movement (*i.e.* the smallest head position change, which should be defined as movement), the error of the AG system was taken into consideration.¹¹ This error was observed to be up to 0.25° in all axes. Thus, the threshold for defining movement (gold standard for movement) was set to ≥0.3°, representing a change in head position ≥0.5 mm as measured at the patient's nose tip, considering an average distance of 100 mm in the axial plane between the AG and the nose tip.¹¹ Movement complexity was defined, based on which axes/planes were affected by the movement, to be uniplanar (*i.e.* when movement involved one plane: head lifting and anteroposterior translation) or multiplanar (*i.e.* when movement involved more than one plane: nodding, swallowing, and lateral head rotation).¹¹

Image quality and interpretability

Three independent observers, specialists in dentomaxillofacial radiology working with CBCT for several years, were informed of the indication of the CBCT examination (diagnostic task), but were blinded according to the true state of movement in a patient. Also, they were not aware of the prevalence of moving patients in the sample. Images were assessed on a 24-inch flat screen monitor (Dell P2412H, Dell Inc., Round Rock, TX) using dedicated software (OnDemand 3D, CyberMed, Seoul, South Korea) in a room with dimmed light. The same windowing settings (L = 848, W = 4340) were used for all cases. The observers could navigate in freely chosen planes through the volumes. Observers

Table 1 Prevalence and distance of patient movement (count) related to age group, diagnostic task and movement complexity

Movement distance (mm)	Age (years)			Task			Movement complexity	
	≤15	16–30	≥31	IUC	I3M	Endo	Uniplanar	Multiplanar
No movement	2	16	10	2	20	6	0	0
≥0.5<1.0	5	17	13	4	26	5	27	8
≥1.0<2.0	21	23	14	17	27	14	26	32
≥2.0<3.0	12	6	4	12	5	5	4	18
≥3.0<4.0	5	2	3	6	1	3	3	7
≥4.0	7	0	2	7	0	2	0	9
Total	52	64	46	48	79	35	60	74

IUC, impacted upper canine; I3M, lower third molars.

scored: the presence of stripe (*i.e.* streak) artefacts in the images (absent; “enamel stripes” related to the presence of dental hard tissues; “metal stripes” related to metal/radiopaque material; “movement stripes” related to patient movement), the presence of overall unsharpness (absent; present) and image interpretability (interpretable; not interpretable). To avoid observer fatigue, scoring sessions were limited to 1 h in a day. Further, the sequence of cases to be scored was different for each observer.

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 Kappa statistics. Patient movement prevalence and distance as defined by AG was initially related

to diagnostic task, patient’s age group (≤15, 16–30, ≥31 years old) and movement complexity (uniplanar or multiplanar). Age groups were defined based on the observation of “age-clusters” in the evaluated sample, which would compromise the use of patient’s age as a continuous variable. For all observers individually, cross-tables were made for the relationship between presence of “movement stripes”, presence of overall unsharpness, image not interpretable and the true movement distance and complexity read-out from AG. Similarly, the relationship was calculated between presence of “metal artefacts”, presence of overall unsharpness, image not interpretable and the true presence of metal/radiopaque material in the FOV. χ^2 tests were initially used to test whether image quality and interpretability were dependent on movement distance, movement complexity and presence of metal/radiopaque material in the FOV affected.

Table 2 Relationship between movement distance and the presence of stripe artefacts related to movement, overall unsharpness and image interpretability, for each observer

Observer	Movement distance (mm)	Movement stripes			Unsharpness			Image interpretability		
		Absent	Present	χ^2	Absent	Present	χ^2	Interpretable	Not interpretable	χ^2
1	No movement	18	10	0.045	18	10	0.001	24	4	0.007
	≥0.5<1.0	27	8		31	4		32	3	
	≥1.0<2.0	33	25		41	17		50	8	
	≥2.0<3.0	12	10		12	10		19	3	
	≥3.0<4.0	3	7		3	7		6	4	
	≥4.0	3	6		3	6		4	5	
2	No movement	11	17	0.345	16	12	0.001	26	2	0.015
	≥0.5<1.0	12	23		27	8		33	2	
	≥1.0<2.0	19	39		33	25		47	11	
	≥2.0<3.0	5	17		10	12		17	5	
	≥3.0<4.0	1	9		1	9		6	4	
	≥4.0	1	8		2	7		5	4	
3	No movement	14	14	0.053	11	17	0.052	24	4	0.019
	≥0.5<1.0	20	15		22	13		35	0	
	≥1.0<2.0	23	35		28	30		50	8	
	≥2.0<3.0	8	14		5	17		18	4	
	≥3.0<4.0	4	6		3	7		8	2	
	≥4.0	0	9		3	6		5	4	

Table 3 Relationship between movement complexity and the presence of stripe artefacts related to movement, overall unsharpness and image interpretability, for each observer

Observer	Movement complexity	Movement stripes			Unsharpness			Image interpretability		
		Absent	Present	χ^2	Absent	Present	χ^2	Interpretable	Not interpretable	χ^2
1	No movement	18	10	0.464	18	10	0.045	24	4	0.526
	Uniplanar	38	22		47	13		52	8	
	Multiplanar	40	34		43	31		59	15	
2	No movement	11	17	0.484	16	12	0.001	26	2	0.073
	Uniplanar	18	42		45	15		52	8	
	Multiplanar	20	54		28	46		56	18	
3	No movement	14	14	0.339	11	17	0.054	24	4	0.298
	Uniplanar	28	32		34	26		55	5	
	Multiplanar	27	47		27	47		61	13	

All cases characterized by each observer as “not interpretable” were further analysed in a descriptive manner. Relevant risk factors ($p \leq 0.20$ from the χ^2 test) were then entered into a multivariate logistic regression analysis with “not interpretable” as the outcome (level of statistical significance was $p \leq 0.05$). For this step, based on the data distribution, true movement distance was recoded to into five categories instead of the original six: no movement, $\geq 0.5 < 1$, $\geq 1 < 2$, $\geq 2 < 3$, ≥ 3 mm, before entered as an independent variable. The analyses were performed for each observer separately.

Results

According to AG, in 134 (82.7%) of the examinations, movement ≥ 0.5 mm was present. The head movements ranged from 0.5 to 6.9 mm (approximately), measured at the patient's nose tip. Considering the patients who moved, approximately 26% moved less than 1 mm, 43% between 1 and 2 mm, 16% between 2 and 3 mm, 7.5% between 3 and 4 mm and 7% moved 4 mm or more. In 74 (45.7%) of the examinations with movement, multiplanar movement was present. The prevalence and distance of patient movement related to age group, diagnostic task, and complexity is presented in Table 1.

Interobserver agreement for stripe artefacts was fair for “enamel stripes” (0.26, on average) and “movement

stripes” (0.33), while it was good for “metal stripes” (0.64). Interobserver agreement was fair regarding overall unsharpness (0.26, on average) and good for image interpretability (0.65, on average). Regarding image interpretability, there was full agreement among the three observers in 137 (85%) of the cases. From the observers' scores, the vast majority (97.5–98.1%) of the images presented stripe artefacts, which were in most cases of combined types. Observers scored that 88.9% (79.6–95.7) of the images presented “enamel stripes”, 30.8% (22.8–40.1) presented “metal stripes” and 56.0% (40.7–69.8) presented “movement stripes”. Observers further scored 44.7% (33.3–55.6) of the images with overall unsharpness. Observers scored 15.9% (13.6–17.3) of the images as “not interpretable”.

Considering movement distance (Table 2), two observers obtained a significant relationship ($p \leq 0.05$) between movement and the presence of “movement stripes”, while the relationship between movement and overall unsharpness was significant ($p \leq 0.05$) for all observers. The relationship between presence of movement and the image being not interpretable was also significant ($p \leq 0.05$) for all observers. Movement complexity was significantly ($p \leq 0.05$) related to the presence of overall unsharpness in the image, but not to the presence of “movement stripes” and image interpretability, as presented in Table 3. The relationship between presence of metal/radiopaque material in the FOV, and the presence of “metal stripes” ($p \leq 0.001$) and image interpretability was significant ($p \leq 0.01$) for all

Table 4 Relationship between presence of metal/radiopaque material in the FOV and the presence of stripe artefacts related to metal, overall unsharpness and image interpretability, for each observer

Observer	Metal	Metal stripes			Unsharpness			Image interpretability		
		Absent	Present	χ^2	Absent	Present	χ^2	Interpretable	Not interpretable	χ^2
1	Absent	110	4	<0.001	77	37	0.715	102	12	0.001
	Present	15	33		31	17		33	15	
2	Absent	91	23	<0.001	69	45	0.028	100	14	0.009
	Present	6	42		23	29		34	14	
3	Absent	107	7	<0.001	60	54	0.001	104	10	0.006
	Present	10	38		12	36		36	12	

observers, although the same result ($p \leq 0.05$) was found only for two observers regarding overall unsharpness (Table 4).

In view of the sample as a whole, the number of cases in which the observers stated that the images were “not interpretable” ranged from 22 to 28, and the characteristics (*i.e.* movement distance and presence of metal in the FOV) of these cases are presented in Table 5. From the table, it may be seen that there is not always a clear “threshold” for when movement distance will definitely lead to a non-interpretable image. The majority of the cases with no metal/radiopaque material in the FOV scored as “not interpretable” were for IUC. In these cases, the median recorded movement distance was $\geq 2 < 3$ mm. Two cases with no movement and no metal/radiopaque material in the FOV were scored as “not interpretable” by two observers. In one of these cases, CBCT was requested for IUC, and in the other for Endo. When metal/radiopaque material was present in the FOV, the median recorded movement distance in the cases scored as “not interpretable” was $\geq 1 < 2$ mm. Such characteristics were most commonly present in the cases requested for Endo. Examples of cases scored as non-interpretable are presented in Figures 1 and 2.

“Not interpretable” was further explored in the multivariate logistic regression analyses (Table 6), where movement distance and presence of metal/radiopaque material in the FOV qualified for inclusion as independent risk factors. The risk that an image was scored as “not interpretable” was highly associated with movement distance. For small movements (*i.e.* < 3 mm) there was no statistically significant impact on image interpretability. On the other hand, for movement distance ≥ 3 mm, the risk that a case was scored as “not interpretable” was 3.2 to 11.3 (95% CI [0.70–65.47]) times higher than in cases without patient movement. In these cases (movement distance ≥ 3 mm), the increased risk was statistically significant ($p \leq 0.05$) for two of the observers. For all observers, the presence of metal/radiopaque material in the FOV had an impact ($p \leq 0.05$) [OR range 3.61–5.05; 95% CI range: 1.60–13.09] on image interpretability.

Discussion

The lack of accurate and objective patient tracking methods makes it challenging to establish a causal relationship between patient movement characteristics and loss of image quality in CBCT sections, which in the end of the chain hampers image interpretability. In that direction, less subjective reference standards for movement definition are needed. To the best of our knowledge, the present study is the first to use a three-dimensional approach to record patient head movement and use these data to assess the impact of specific movement characteristics (*i.e.* distance and complexity) on image quality. The study was prospective in the design for data collection, *i.e.* the method was defined prior

Table 5 Characteristics (task, age, movement distance, presence of metal/radiopaque material in the FOV) of the cases scored as “not interpretable”, for each observer

Obs	Task	Age (years)	Cases without metal in the FOV					Cases with metal in the FOV							
			Movement distance (mm)					Movement distance (mm)							
			16-30	≥31	No mov	≥0.5 <1.0	≥1.0 <2.0	≥2.0 <3.0	≥3.0 <4.0	≥4	No mov	≥0.5 <1.0	≥1.0 <2.0	≥2.0 <3.0	≥3.0 <4.0
1 (n = 27)	IUC	10	-	-	1	-	2	1	2	4	-	-	-	-	-
	I3M	-	3	-	-	1	-	-	-	-	-	2	-	-	
	Endo	1	-	13	1	-	-	-	-	-	1	2	5	2	1
2 (n = 28)	IUC	13	-	-	1	1	3	2	2	4	-	-	-	-	-
	I3M	-	1	1	-	-	-	-	-	-	-	1	1	-	-
	Endo	-	-	13	-	-	1	-	-	-	-	1	6	3	2
3 (n = 22)	IUC	9	-	-	1	-	2	2	1	3	-	-	-	-	-
	I3M	-	1	1	-	-	-	-	-	-	1	-	1	-	-
	Endo	-	-	11	1	-	-	-	-	-	1	-	5	2	1

Figure 1 Case scored as “not interpretable” by all three observers as seen in the sagittal, coronal and axial planes. The diagnostic task was the evaluation of resorption of teeth adjacent to an IUC. There was no metal/radiopaque material in the FOV, and the patient performed a large (approximately 3.5 mm in distance) uniplanar movement. Stripe artefacts (mostly in the axial plane image) and overall unsharpness (*i.e.* double contours) can be seen in the images. FOV, field-of-view; IUC, impacted upper canine.

Figure 2 Case scored as “not interpretable” by all three observers as seen in the sagittal, coronal and axial planes. The diagnostic task was possible endodontic problem. There was metal/radiopaque material in the FOV, and the patient performed a 2.8-mm multiplanar movement. Several stripe artefacts (mostly in the axial plane image) and overall unsharpness can be seen in the images. FOV, field-of-view.

to the study and followed through all patient examinations; while the scoring of the CBCT volumes was retrospective, *i.e.* performed after all movement data were collected.

CBCT reconstruction algorithms do not consider the existence of possible patient movements, and no information on such entity is recorded nor integrated in the reconstruction algorithms.^{1,3} Before this can be pursued, well-defined methods for detecting patient movement in all planes must be developed. Following this demand, we have recently suggested an objective three-dimensional approach to register patient head movements based on an AG tracking system.¹¹ Recently, a second objective method has been developed, which is based on the use of three cameras able to track the position of a dot pattern mounted on a headband worn by the patient during the examination; however this has only been tested *ex vivo*.¹² If such methods are implemented in the clinic, they may serve two purposes: initially, help to decide when to interfere with the examination (*i.e.* the operator should stop, reinstruct the patient and repeat the examination or thresholds implemented for automatic termination of the examination); secondly, in image reconstruction algorithms able to provide CBCT motion artefact correction.^{1,3,13,14}

If the patient moves during a CBCT examination, artefacts that arise in the final images are usually seen as stripes/streaks, double contours or overall unsharpness.^{5,15} In extreme cases, the presence of such artefacts would render images that are uninterpretable (*i.e.* trained observers will be unable to make a report based on the images).^{1,10} In a recent study, based on a sample that partially overlaps the one used in the present study, we suggested that movements with certain characteristics (repeated movement, with a long duration, and

multiplanar) are often related to impaired CBCT image quality.¹⁰ In opposition to our previous study,¹⁰ the present results point towards the fact that distance may be the most relevant movement parameter influencing image quality and interpretability. Image quality was hampered whenever movement was present, but only when the movement was ≥ 3 mm, the risk that an image was scored as “not interpretable” was statistically significant. If AG is used to track patient movement in real time, this distance could be suggested as a threshold to abort an examination, which would lead to a non-interpretable image, since approximately 50% of the examinations with movement ≥ 3 mm were scored as “not interpretable”.

Also opposing to our previous study,¹⁰ movement complexity was not a significant parameter affecting image quality and interpretability, and did not qualify for inclusion in the regression analyses. A reasonable explanation for such difference is the reference standard for defining movement. In the present study, position changes recorded by AG defined the movements. Accelerometers and gyroscopes are classified as inertial sensors, which can be used for motion tracking.¹⁶ According to the literature, 75% of movements between 1 and 2 mm detected by AG are not detected by video observation.¹¹ This means that the prevalence of moving patients in the present study was much larger than that previously reported. One can speculate that the definition of more specific parameters, such as movement distance and complexity, would then also be affected.

Another possible explanation is the fact that in the previous study,¹⁰ only patients with no metal/radiopaque material in the FOV were included. Attention must be paid to various types of artefacts, such as beam-hardening and extinction artefacts, which can be seen in CBCT

Table 6 Multivariate logistic regression analyses (162 CBCT examinations) for the impact of movement distance and presence of metal/radiopaque material in the FOV on the variable “not interpretable” (outcome). Variables in parentheses served as reference

Variables	<i>p</i>	<i>OR</i>	<i>95% CI</i>
Observer 1			
Movement distance (mm) (absent, <i>n</i> = 28)			
≥0.5<1.0	0.423	0.51	0.10–2.65
≥1.0<2.0	0.856	0.88	0.23–3.41
≥2.0<3.0	0.943	1.06	0.20–5.74
≥3	0.011	6.97	1.57–30.98
Metal/radiopaque material (absent, <i>n</i> = 114)			
Present	0.001	5.05	1.95–13.09
Observer 2			
Movement distance (mm) (absent, <i>n</i> = 28)			
≥0.5<1.0	0.784	0.75	0.10–5.85
≥1.0<2.0	0.179	3.01	0.60–15.10
≥2.0<3.0	0.102	4.48	0.74–27.01
≥3	0.007	11.29	1.95–65.47
Metal/radiopaque material (absent, <i>n</i> = 114)			
Present	0.006	3.61	1.45–8.98
Observer 3			
Movement distance (mm) (absent, <i>n</i> = 28)			
≥0.5<1.0	nd	nd	nd
≥1.0<2.0	0.866	0.89	0.23–3.41
≥2.0<3.0	0.605	1.52	0.31–7.34
≥3	0.133	3.17	0.70–14.32
Metal/radiopaque material (absent, <i>n</i> = 114)			
Present	0.004	4.31	1.60–11.60

sections simultaneously.^{2,3} It has been suggested that even small amounts of metal in the FOV can cause changes in CBCT images, considering the typical kilovoltage applied in CBCT machines.³ In the present study, when comparing cases with and without metal/radiopaque materials in the FOV, relevant differences were seen regarding the presence of “metal stripes”, overall unsharpness and image interpretability. The amount of metal/radiopaque material in the cases varied, and cases even with small amounts of material were included in the metal/radiopaque material group. In the results of the multivariate logistic regression analysis, metal/radiopaque material in the FOV was also a highly significant parameter with impact on image interpretability. Supporting the impact of such artefacts, there were approximately two cases (depending on observer) with metal/radiopaque material in the FOV, but with no movement, that were scored as non-interpretable (for a total of 15 cases with metal/radiopaque material, which the observers scored as “not interpretable”). There were also cases, in which neither movement nor metal/radiopaque material was present in the FOV (one to two cases,

depending on observer). This might be connected to the fact that a major factor defining an image as non-interpretable is the presence of heavy stripe artefacts, some of which are related to enamel, particularly in bony impacted teeth. These artefacts are often more visible in the axial sections, and for IUC they are commonly located in the same plane, in which a possible resorption of the lateral tooth/premolar is to be interpreted.¹⁰

Another possibility for the non-interpretable cases with no metal and no (or very small) movement could be the number of movements performed during the examination. A previous study stated that the accumulated number (*i.e.* more than three isolated movements during the examination) impaired image quality.¹⁰ In that study, cumulative count was possible since video observation was used to identify patient movements, and large and well defined (*i.e.* visible) movements were counted. In the present study, we focused on the “worst” movement (*i.e.* largest distance), which took place during the examination, rather than counting isolated movements. The AG recording method is a fully dynamic and continuous registration of changes in head position throughout the examination period, making it very difficult to define when one movement ends and the next one starts; thus isolated movements cannot be counted separately. It cannot be ruled out that in these two to three cases several small (*i.e.* smaller than the threshold for movement definition) movements were present, also hampering image quality.

From the present results, two tendencies can be observed. One refers to the patient’s age group, which is also related to the requested diagnostic task. Young patients (*i.e.* younger than 15 years) are known to move more often than older patients.¹⁷ This is the age group in which the main requested diagnostic task was the evaluation of possible resorption of teeth adjacent to an IUC. In this way, in the present study, it is impossible to speculate which factor is more relevant—the age group or the diagnostic task. Another well-defined tendency is that, for the older patients (*i.e.* equal to or older than 31 years), the presence of metal/radiopaque material in the FOV was more relevant for an image being scored as “not interpretable” than the presence of patient movement itself. A previous study reported that in this age group the prevalence of moving patients is small.¹⁷

To the present, this is the first study to suggest possible distance thresholds, above which a certain movement implies a high risk that the diagnostic outcome of an examination is affected. In the future, this information could be used to decide when to interact with the examination, *i.e.* stop and reinstruct the patient or repeat the examination. To provide rationale on when to take such decision, more knowledge on the relationship between movement distance and complexity and the impact on image quality must be provided, although. Ideally, movement characteristics should be tested through *ex vivo* setups in diagnostic accuracy studies, considering diverse diagnostic tasks, and in which a robot

simulates various patient movements. In such studies, the diagnostic accuracy of CBCT images acquired with known movements must be checked against a solid reference standard for disease. Such studies would elucidate in detail the relationship between movement characteristics and the possibility to reach a correct diagnosis.

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Conclusion

The presence of patient movement ≥ 3 mm and presence of metal/radiopaque material in the FOV had significant impact on CBCT image quality and interpretability. Movement complexity had no significant impact on the assessed parameters.