

**Reducing CBCT radiation dose and maintaining image quality for reliable
cephalometric measurements – proof of concept**

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Abstract

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Introduction: CBCT is increasingly used as tool for orthodontic diagnosis, either as an adjunct or replacement to traditional imaging techniques. Methods to reduce the increased CBCT radiation doses by optimizing exposure settings are essential for the orthodontic patient population. **Methods:** A human cadaver was scanned in the Morita Accuitomo 170® CBCT machine under the manufacturer recommended settings (5mA, 90kV, 360°) and multiple combinations of decreased exposure settings: 1, 2.5, 5 mA - 60, 70, 80, 90 kV - 180° and 360° rotation arc. Radiation dose was recorded for each exposure setting. Ten examiners (3 faculty, 7 residents) identified anatomic landmarks on 24 reconstructed cephalometric images and 7 cephalometric values were recorded. Measurement errors were compared and matched by exposure settings. **Results:** No significant differences in measurement errors were observed between 360° -180° rotation, 5mA - 2.5mA, 90kV - 80kV images. The radiation dose was reduced by 50% when mA was lowered to 2.5mA instead of 5mA and by 45% when the rotation arc was 180° instead of 360°. The lowest settings (1mA or 60kV) had increased error and were considered non-diagnostic. **Conclusions:** Orthodontists can lower the CBCT exposure settings in order to greatly reduce radiation dose and still maintain sufficient image quality for cephalometric diagnosis.

INTRODUCTION

Cone Beam Computed Tomography (CBCT) imaging is increasingly used as a tool in orthodontic diagnosis and treatment planning, either as an adjunct or substitute for the panoramic and cephalometric radiographs. Both the European Commission guidelines and the American Association of Oral and Maxillofacial Radiology (AAOMR) clinical recommendations clearly specify that routine CBCTs are not indicated for the orthodontic patient due to the risk of unnecessary ionizing radiation^{1,2}.

The CBCT technology produces consistently and considerably higher radiation doses when compared to conventional 2D radiography. Children are more susceptible to ionizing radiation than adults due to the high number of dividing cells (risk of DNA mutagenesis) and their longer expected life span which increases the risk of expressing any radiation-induced effects.³ As a result, X-ray hygiene in orthodontics is a crucial concern in the context of the young orthodontic population. Clinicians should also keep in mind that manufacturer's settings designed for adults may result in excessive radiation exposure if used on smaller and younger patients.⁴

The assessment of risks associated with the use of radiation for diagnostic imaging is a public health issue and studying patient dose optimization by reduction of exposure factors (kV, mA, resolution, FOV and arc of rotation) is among the most recommended research priorities.¹

Radiation dose varies according to the device as exposure parameters like amperage, voltage and degree of rotation differ. Milli-amperage (mA) determines the quantity of photons, hence an increase in mA, results in an increased radiographic density, which subsequently produces sharper images. The radiation dose increases proportionately in a linear fashion with the mA setting (e.g. 5mA results in double the dose of an exposure made at 2.5mA and vice

versa). The kilo-voltage (kV), on the other hand, controls the penetrating power of the x-ray beam and lowering the kV will result in an image with reduced contrast. The radiation dose to the patient is directly proportional to the square of the kV (exponential relationship).⁵ Regarding the rotation arc, the X-ray tube usually rotates 360° around the patient's head and some machines have the option to reduce the rotation arcs to 180°-220°. Pauwels et al. estimated that the use of a 180° rotation arc results in an average dose reduction of 45% when compared to full rotation, but with images being slightly grainier.⁶

Lowering one or all of the above parameters leads to decreased radiation dose, producing however, a proportionally decreased image quality. It is beyond doubt that radiation dose reduction should be evaluated together with image quality and that the images should be diagnostic for the purpose they are being made.

The main objective of this study was to investigate the relationship between modifying CBCT exposure settings (mA, kV and rotation arc) and image quality. The purpose was to find the exposure settings that reduce radiation dose and maintain the image quality at a level that is appropriate and sufficient for cephalometric orthodontic diagnosis. The specific aim was to compare the reliability of cephalometric measurements performed on cephalograms extracted from CBCT scans taken at manufacturer recommended settings and from CBCT scans obtained under lowered kV, mA and degrees of rotation. The reliability of cephalometric measurements was assumed to be a surrogate for image quality. A second goal was to record the radiation dose reduction in specific parts of the head and neck when these exposure settings were lowered, compared to the manufacturer's recommended settings.

MATERIAL AND METHODS

An embalmed male cadaver was sectioned horizontally at nipple level to enable head scans. The cadaver was scanned multiple times under altered exposure settings using a clinical CBCT machine (3D Accuitomo 170 J. Morita MFG. Corp, Japan). The cadaver was selected from the university's human anatomy lab. The selection criteria were to have as many teeth present as possible to provide dental landmarks, to have the least amount of prosthetic work to avoid major scanning artifacts, to have no fractures, to have no obvious asymmetries or large deviations from normal anatomy. The cadaver, sectioned at nipple level, was maintained in the same position during all the CBCT scans, facilitated by the fact that the specimen had been injected with fixative for later dissection.

The manufacturer recommended settings for this CBCT machine (5mA, 90kV, 360°) were used for the first scan. Subsequently the following exposure combinations (mA, kV and rotation arc) were used, without moving the cadaver:

- mA: 5, 2.5 and 1
- kV: 90, 80, 70 and 60 kV
- rotation arc: full rotation (360°, 17.5 sec exposure time) and half rotation (180°, 9 sec exposure time).

This resulted in a total of 24 scans. All CBCT scans were taken at a resolution of 0.27mm slice thickness/voxel size and a field of view of 170x120mm which included the cranial base, the entire maxilla and a part of mandible. Because of the cadaver's neck position, the mandible could not be entirely included in the scan volume. A traditional two dimensional cephalogram was also taken (Planmeca Promax, Dimax 4) at standard manufacturer's settings (70 kV at 13 mA) with the cadaver's left side towards the X-ray tube.

For the dosimetry, skin radiation dosimeters, with minimal reception capability of 0.050mGy or 50microSv, that use optically stimulated luminescence (OSL NanoDot, Landauer, IL) were placed on the right eyelid, the right parotid area, and anterior to the thyroid gland. These receptors did not interfere with the image quality nor did they cause artifacts. They were changed for each new acquisition. Three dosimeters were not exposed and were used as controls. The dosimeters were sent back in the appropriate fashion to the manufacturing company (Landauer, IL) and the dosimetry results were received by e-mail.

The 3D volumes were imported in DICOM format to the Dolphin®3D imaging system for further processing. Because the original position of the head in all the CBCT images was the same but tilted to one side, the volumes had to be standardized and re-oriented in Dolphin® to reproduce the position as if in a conventional cephalostat. The right Frankfort plane was oriented parallel with a horizontal line (assessed in a sagittal view to set the line between the anterior and posterior nasal spine perfectly horizontal or no “pitch”). The line passing between right and left Porion was oriented parallel with a horizontal line (assessed in frontal view to assure a vertical position of the mid-sagittal plane or no “roll”). The mid-sagittal plane was oriented vertically in axial view to assure there were no rotations around the vertical axis or no “yaw”. Using the Dolphin® software, a digital cephalometric 2D image was extracted from each of the 24 standardized 3D volumes (Fig.2). These images were de-identified for exposure parameters prior to interpretation in order to avoid examiner bias.

Ten observers (7 orthodontic graduate students and 3 orthodontic faculty members) participated in the study anonymously. After an instruction session, they identified the following anatomical landmarks on the 24 CBCT cephalometric images: Sella, Nasion, Porion, Orbitale,

anterior nasal spine (ANS), posterior nasal spine (PNS), A-Point, maxillary central incisor (U1) incisal tip, maxillary central incisor (U1) root tip (see appendix for definitions). All observers agreed on the given definitions and examined the cephalograms blinded to scanning parameters one image at a time, with at least two days between examinations to prevent examiner fatigue and recognition of landmarks. The observers calibrated each image by identifying two landmarks on a 100mm digital ruler. The images were provided in the order of the overall radiation dose, from low to high known only by the main investigator who did not take part in the measurements. Four images (90kV/5mA/360°, 90kV/2.5mA/360°, 90kV/2.5mA/180°, 60kV/1mA/360°) were repeated and randomly inserted among the others in order to obtain double measurements to assess intra-examiner reliability. To minimize external variation, the observers used the same two computers in the same room under the same lighting conditions each time. They were allowed to use enhancement options (contrast, brightness, sharpness) and could not look at previously digitized images.

A customized cephalometric analysis was created in Dolphin® which included the following skeletal and dental measurements: SNA angle, S-N line (mm), A-N perpendicular distance (mm), U1 / N-A (mm and degrees), U1 / S-N (degrees), U1 / PP (palatal plane, degrees) -see appendix for list of definitions. Subsequently, the measurement values were digitally extracted directly from Dolphin® avoiding any manual calculation (Fig. 3). The data derived from these 7 cephalometric measurements were used for further statistical analysis.

Statistical analysis

The image quality was evaluated through the measurement error calculated as the mean absolute deviation (the mean of the absolute differences of the 10 orthodontists' measurements from the mean of all 10 measurements). A large error value would indicate that the

measurements of that particular parameter varied widely among examiners for that image, with the implication being that the image (and thus the radiograph settings used to create that image) was not optimal. Small absolute deviation values would indicate that the orthodontists were in better agreement and thus the image considered more suited for orthodontic diagnosis.

Acquisition settings were compared with respect to measurement error using a paired permutation-test. It was assessed whether the difference between the paired errors was statistically significantly different from zero using a permutation procedure (permuting the group membership within each pair) with 10,000 Monte-Carlo permutations.⁷ The permutation test is a general test comparing two groups (means of absolute deviation in our case) and is similar in this sense to a paired t-test. The data were analyzed with R language for statistical computing.⁸ R is a computer language used for data manipulation and statistical computing.

Inter-observer error among raters was calculated using a similar computation (the average absolute deviation from the mean). Intra-observer error was analyzed on the basis of double measurements using Dahlberg's formula. For the analysis of the radiation dosimetry data, Medcalc® statistical software version 17.4 was used (Medcalc Software, Ostend, Belgium, 2017, <http://www.medcalc.org>).

This study was approved by the institutional review board approval (#49649).



Figure 1. The CBCT machine - 3D Accuitomo 170 J. Morita MFG. Corp, Japan.

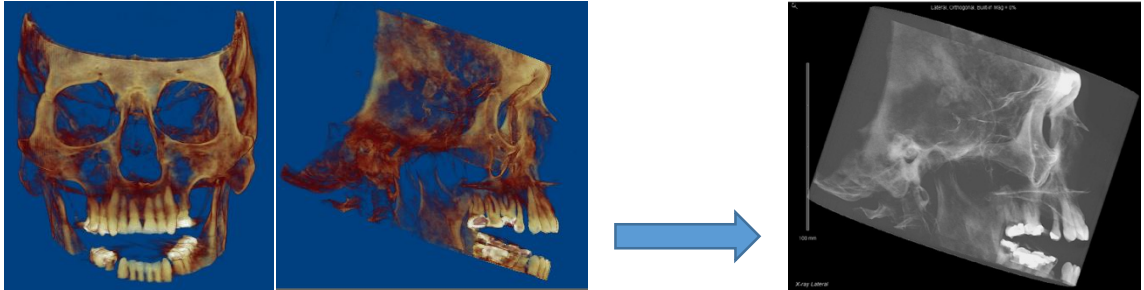


Figure 2. Re-oriented CBCT volume and extracted cephalogram

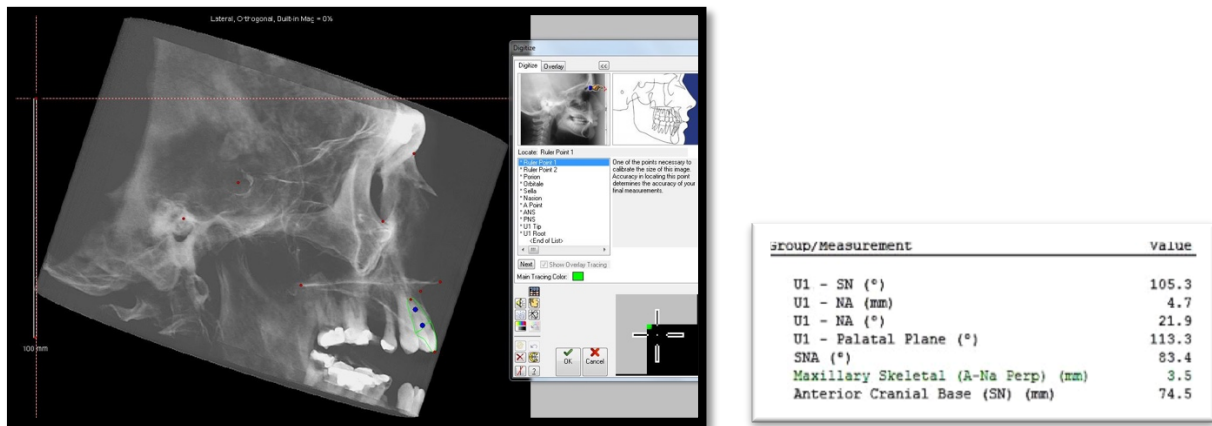


Figure 3. Digitized landmarks and automated measurements using Dolphin®

RESULTS

Measurement values are presented in Table I with means and error (mean absolute deviation). It was observed that image #9 (360°, 1mA, 70kV) had an increased number of outliers and a high absolute deviation compared to the other images. The image proved to be defective due to distortion during acquisition, and was therefore removed from further statistical analyses.

Images became grainier as mA was modified to 1mA (Fig. 4) and the error of measurements had a tendency to increase as mA was decreased from 5mA to 2.5mA and further to 1mA especially in the case of A-N perp (mm), SN (mm), U1-NA (mm) and SNA. This trend illustrates the impact of lowering the mA on the image quality and the reliability of some of the measurements (see Fig. 5). Other measurements such as U1-NA (deg), U1-PP (deg) and U1-SN (deg) seemed to be regardless of the mA. The measurements on the traditional cephalogram showed a high spread, with the exception of SN (mm).

Considering the mean of each measurement for each image to be the reference, measurements conducted on 5mA and 2.5mA images had overall the highest reliability (Table II). It was observed that all measurements conducted on images at 1mA had increased error (“absolute deviation”) when compared to the 2.5 and 5mA images, and almost all of these proved to be statistically significant (statistical significance at $p < 0.05$, Table III, permutation tests). This indicates that the lower quality of the 1mA images is significantly associated with higher error in landmark identification. When compared with the 5mA images, three of the measurements at 2.5mA were statistically worse: A-N perp, U1-NA distance and U1-NA angle. However, the absolute differences between the error of these measurements at 5mA and 2.5mA were minimal (0.15mm for A-N perp, 0.21mm for U1-NA distance, 0.53° for U1-NA angle).

Image quality was similar at 90kV and 80kV and tended to decrease at 70kV and 60kV (Fig. 6). The spread of cephalometric measurements increased as kV was decreased from the recommended 90kV to 80kV to 70kV and subsequently further down to 60kV. This was obvious especially for A-N perp (mm), SN (mm), U1-NA (mm), SNA (deg) as can be seen on the graphs in Fig 7. This trend suggested the detrimental impact on reliability of measurements when decreasing the kV to 60kV. The measurements from the traditional cephalogram also showed a high spread with the exception of SN (mm).

Measurements conducted on the 90kV and 80kV images had the highest reliability and they were similar to each other (Table IV). There were no statistically significant differences between images taken at 90kV versus 80kV ($p < 0.05$) suggesting that these two exposure settings are comparable in quality (Table V.). The 70kV images also had a high reliability, with the exception of SN (mm) with a deviation of 0.42mm compared to 0.34mm (80kV) and 0.28mm (90kV), which proved to be statistically significant.

The measurement error increased as the kV decreased to 60kV. When comparing with the 80kV and 90kV images (Table V.), almost all 60kV images had increased error values that were statistically significant ($p < 0.05$), suggesting that these images were less reliable for measurements.

Images taken at 180° rotation arc were grainier but similar when put side by side with the 360° images (Fig. 8). According to the graphic representations of the cephalometric values, the measurement error had no overall recognizable trend when the rotation arc was modified from 360° to 180° degrees (Fig. 9). This suggests that the rotation arc did not impact greatly the reliability of measurements. All the outliers in the Fig.7 are from images taken at 1mA which seems to greatly impact the quality of image and skew the results more than the arc of rotation

does. The measurements conducted on the traditional cephalogram showed a high spread with the exception of SN distance (mm).

The absolute deviations were similar in value for 180° and 360° (Table VI.). There were two statistically significant differences between measurements performed on images taken at 360° versus 180° degrees: A-N perp and U1-NA distance. The error for A-Nperp was on average 0.25mm more as opposed to 360° and the error for U1-NA distance was 0.34mm more when compared to 360°.

There was no evidence of disparity among examiners. The differences between residents and faculty measurements were non-significant (Table VII -permutation tests). Intra-examiner reliability analysis (Table VIII.- Dahlberg's formula) shows that examiners' reliability depended on the image quality and the measurement type. Higher quality images and measurements like SN(mm), SNA (deg), U1-PP (deg) had the highest examiner reliability. Measurements like A-N perp (mm) and U1-NA (mm) had lower reliability which corresponded with their inherent coefficient of variance.

As expected, the radiation dose increased with mA, kV and full rotation (Fig.10). When lowering from 5mA to 2.5mA the radiation dose is reduced to half for the eyelid and the parotid gland and there is an exponential decrease of radiation along with kV (Fig. 10.A.,B).

The absorbed radiation dose was reduced almost to half when the machine was set at 180° instead of 360°. At half rotation, the radiation dose was estimated to be half for the parotid and four-fold reduction for the eyelid sensor. The right eyelid received much less radiation on the 180° rotation setting because it was not exposed directly (out of the trajectory of the X-ray tube on the left side).

The scattered radiation dose for the thyroid was minimal and the sensors captured a minimal amount of radiation in this area only in 4 settings out of 24: 90kv/5mA for both 360° and 180°, 80kv/5ma/360° and 90kv/2.5ma/360°. For the traditional cephalogram, the sensors captured a minimal amount of radiation (50µGy at parotid level).

Image	Exposure settings			A- Nperp (mm)		S-N line (mm)		U1-NA (mm)		SNA (deg)		U1-NA (deg)		U1-PP (deg)		U1- SN (deg)	
	Rotation	mA	kV	Mean	Deviation	Mean	Deviation	Mean	Deviation	Mean	Deviation	Mean	Deviation	Mean	Deviation	Mean	Deviation
1	360°	5	90	3.02	0.67	74.49	0.26	4.65	0.37	82.58	0.48	20.82	1.50	112.36	1.43	103.40	1.60
2	360°	2.5	90	2.85	0.87	74.23	0.27	4.56	0.38	82.63	0.38	20.42	1.22	111.96	1.17	103.03	1.11
3	360°	1	90	2.34	0.96	73.75	0.32	5.30	0.78	82.05	0.42	21.95	1.52	113.03	1.27	103.99	1.43
4	360°	5	80	2.92	0.50	74.49	0.33	4.58	0.50	82.82	0.52	20.45	1.27	112.23	1.18	103.29	1.35
5	360°	2.5	80	2.44	0.79	74.12	0.30	4.51	0.51	82.48	0.42	20.74	1.15	112.18	0.98	103.23	1.14
6	360°	1	80	1.30	1.22	74.49	0.19	4.86	0.61	82.64	0.60	21.20	1.58	112.87	1.43	103.84	1.38
7	360°	5	70	3.21	0.51	74.37	0.48	4.34	0.38	82.81	0.31	21.13	1.17	112.84	1.30	103.94	1.20
8	360°	2.5	70	2.86	0.70	74.54	0.35	4.57	0.71	82.73	0.34	21.41	1.79	113.09	1.61	104.14	1.54
9	360°	1	70	1.07	2.18	71.53	3.29	5.94	0.98	83.70	2.26	22.84	2.06	113.77	2.10	106.54	2.40
10	360°	5	60	2.72	0.60	74.46	0.39	4.49	0.47	82.41	0.39	21.07	1.49	112.76	1.27	103.47	1.33
11	360°	2.5	60	2.84	0.81	74.17	0.41	4.88	0.66	82.43	0.46	21.51	1.83	113.23	1.71	103.95	1.62
12	360°	1	60	1.30	1.46	73.30	1.17	6.03	0.94	82.36	0.94	22.49	3.00	113.12	2.87	104.85	2.81
13	180°	5	90	3.10	0.56	74.28	0.27	4.58	0.42	82.83	0.38	21.31	1.15	112.72	1.26	104.13	1.34
14	180°	2.5	90	2.80	0.72	74.29	0.38	4.44	0.65	82.58	0.41	20.58	1.83	112.23	1.49	103.15	1.68
15	180°	1	90	3.13	1.04	74.00	0.28	4.06	0.56	82.93	0.54	21.74	1.20	113.82	0.98	104.67	1.25
16	180°	5	80	3.00	0.44	74.54	0.45	4.32	0.34	82.64	0.31	21.27	1.35	113.18	1.20	103.89	1.47
17	180°	2.5	80	3.41	0.45	74.14	0.41	4.21	0.51	82.98	0.28	20.54	1.90	112.16	1.73	103.50	1.88
18	180°	1	80	1.67	0.96	74.32	0.34	5.58	1.18	81.70	0.96	21.24	1.60	112.29	1.11	102.94	1.17
19	180°	5	70	2.67	1.00	74.29	0.41	4.41	0.39	82.91	0.27	20.59	0.81	112.78	0.62	103.50	1.00
20	180°	2.5	70	3.65	1.17	74.37	0.26	4.28	0.52	82.98	0.38	19.46	2.11	111.18	1.78	102.45	1.84
21	180°	1	70	1.67	1.27	73.59	0.59	4.56	1.41	82.85	0.86	19.51	1.33	111.37	1.01	102.25	0.80
22	180°	5	60	2.11	0.83	74.77	0.50	4.68	0.30	82.57	0.46	20.25	1.52	111.76	1.36	102.85	1.29
23	180°	2.5	60	2.86	1.10	74.02	0.84	4.30	0.86	82.77	0.55	17.55	2.12	109.71	2.03	100.34	1.94
24	180°	1	60	3.22	2.02	72.68	0.85	5.21	2.23	82.29	1.57	19.97	2.92	112.60	1.70	102.26	1.76
25	Cephalogram			3.36	3.08	74.18	0.58	4.98	1.28	81.79	1.29	21.90	2.20	113.37	2.11	103.78	1.92

Table I: Absolute mean deviations from mean of cephalometric measurements from the 10 examiners for each setting. Two repeat measures were combined for images 1, 2, 12, and 14 which were used for the calculation of the intra-rater reliability.

Mean absolute deviations							
mA	A-N	SN	U1-NA	U1-NA	SNA	U1-PP	U1-SN
	perp	(mm)	(mm)	(deg)	(deg)	(deg)	(deg)
1	1.31	0.59	1.06	1.80	0.85	1.41	1.51
2.5	0.78	0.38	0.61	1.70	0.39	1.53	1.55
5	0.63	0.39	0.40	1.33	0.38	1.25	1.34

Table II. Mean absolute deviations for each measurement according to mA modification

mA	A-N perp (mm)		SN (mm)		U1-NA (mm)		U1-NA (deg)		SNA (deg)		U1-PP (deg)		U1-SN (deg)	
	2.5mA	5mA	2.5mA	5mA	2.5mA	5mA	2.5mA	5mA	2.5mA	5mA	2.5mA	5mA	2.5mA	5mA
1mA	0.0001*	0.0001*	0.03*	0.026*	0.0001*	0.0001*	0.58	0.01*	0.0001*	0.0001*	0.47	0.27	0.78	0.32
2.5mA	-	0.048*	-	0.83	-	0.0004*	-	0.021*	-	0.079	-	0.07	-	0.17

Table III. Monte-Carlo permutation tests: p-values of deviation means when comparing mA settings: 5mA, 2.5mA, 1mA. *Statistical significance at $P < 0.05$.

kV	Mean absolute deviations							
	A-N perp (mm)	SN (mm)	U1-NA (mm)	U1-NA (deg)	SNA (deg)	U1-PP (deg)	U1-SN (deg)	
60	1.17	0.76	0.86	2.05	0.74	1.74	1.78	
70	0.93	0.42	0.68	1.44	0.43	1.27	1.28	
80	0.73	0.34	0.61	1.47	0.51	1.27	1.40	
90	0.73	0.28	0.54	1.41	0.42	1.28	1.38	

Table IV. Means of absolute deviations according to kV modification

kV	A-N perp (mm)			SN (mm)			U1-NA (mm)			U1-NA (deg)		
	70	80	90	70	80	90	70	80	90	70	80	90
60	0.1302	0.0016*	0.0007*	0.0022*	0.0001*	0.0001*	0.1762	0.0517	0.0139*	0.0119*	0.0178*	0.0068*
70	-	0.0993	0.1047	-	0.1212	0.0026*	-	0.3581	0.1602	-	0.8523	0.8393
80	-	-	0.9466	-	-	0.1519	-	-	0.4104	-	-	0.6416

kV	SNA (deg)			U1-PP (deg)			U1-SN (deg)		
	70	80	90	70	80	90	70	80	90
60	0.0044*	0.0303*	0.0025*	0.0158*	0.0271*	0.0257*	0.0089*	0.0758	0.0603
70	-	0.1492	0.7753	-	0.9748	0.9247	-	0.4754	0.5595
80	-	-	0.1134	-	-	0.9586	-	-	0.9005

Table V. Monte-Carlo permutation tests: p-values of error means when comparing kV settings: 90kV, 80kV, 70kV and 60kV. *Statistically significant at $P < 0.05$.

Measurement	Absolute deviation		p-value
	180°	360°	
A-N perp (mm)	1.02	0.77	0.017*
S-N (mm)	13.16	13.00	0.95
U1-NA (mm)	1.08	0.74	0.001*
U1-NA (deg)	3.86	3.75	0.58
SNA (deg)	14.69	14.49	0.95
U1-PP (deg)	20.02	19.96	0.99
U1-SN (deg)	18.38	18.34	0.99

Table VI. Means of absolute error and p-values when comparing 360° with 180°. *Statistically significant at P<0.05.

Measurement	Mean deviations		Difference	95% CI *	p-value
	Residents (n=7)	Faculty (n=3)			
U1-SN (deg)	1.82	1.46	0.36	-0.05 0.90	0.10
U1-NA (deg)	1.85	1.63	0.22	-0.27 0.81	0.35
U1-NA (mm)	0.83	0.64	0.19	-0.09 0.45	0.17
U1-PP (deg)	1.66	1.32	0.35	-0.23 1.02	0.17
SNA (deg)	0.67	0.55	0.12	-0.20 0.44	0.41
A-N perp (mm)	1.02	1.19	-0.17	-0.67 0.31	0.43
SN (mm)	0.69	0.61	0.08	-0.39 0.58	0.74

Table VII. Comparison between examiners: residents and faculty (inter-examiner reliability)

*CI, confidence interval

Measurement	Dahlberg value (% of mean) by image type				All 4 images combined
	90kV/5mA/360°	90kV/2.5mA/360°	60kV/1mA/360°	90kV/2.5mA/180°	
U1-SN (deg)	7.1 (7%)	4.1 (4%)	13 (13%)	5.8 (6%)	8.2 (8%)
U1-NA (deg)	5.7 (27%)	4.4 (21%)	13.5 (64%)	6.5 (31%)	8.3 (40%)
U1 NA (mm)	1.7 (36%)	2 (41%)	6 (125%)	3 (64%)	3.6 (75%)
U1-PP (deg)	6.5 (6%)	4.6 (4%)	11.3 (10%)	5.8 (5%)	7.5 (7%)
SNA (deg)	1.9 (2%)	2 (2%)	6.8 (8%)	2.1 (2%)	3.8 (5%)
A-N perp (mm)	1.4 (55%)	3.2 (122%)	3.7 (143%)	3.6 (138%)	3.1 (120%)
SN (mm)	1.2 (2%)	1.7 (2%)	9.3 (13%)	1 (1%)	4.8 (6%)

Table VIII. Dahlberg's formula value and coefficient of variation by image type

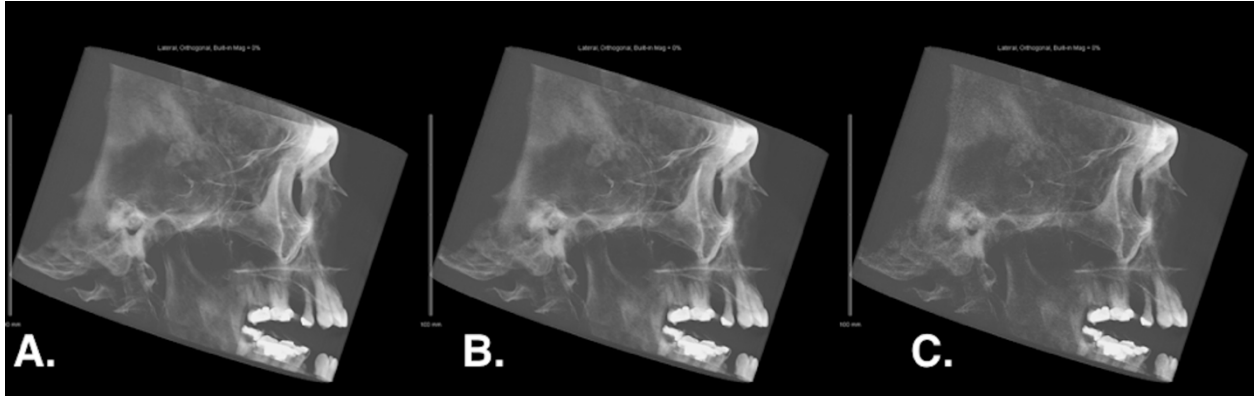


Figure 4. Images taken at: **A. 5mA, 90kV, 360°; B. 2.5mA, 90kV, 360°; C. 1mA, 90kV, 360°**

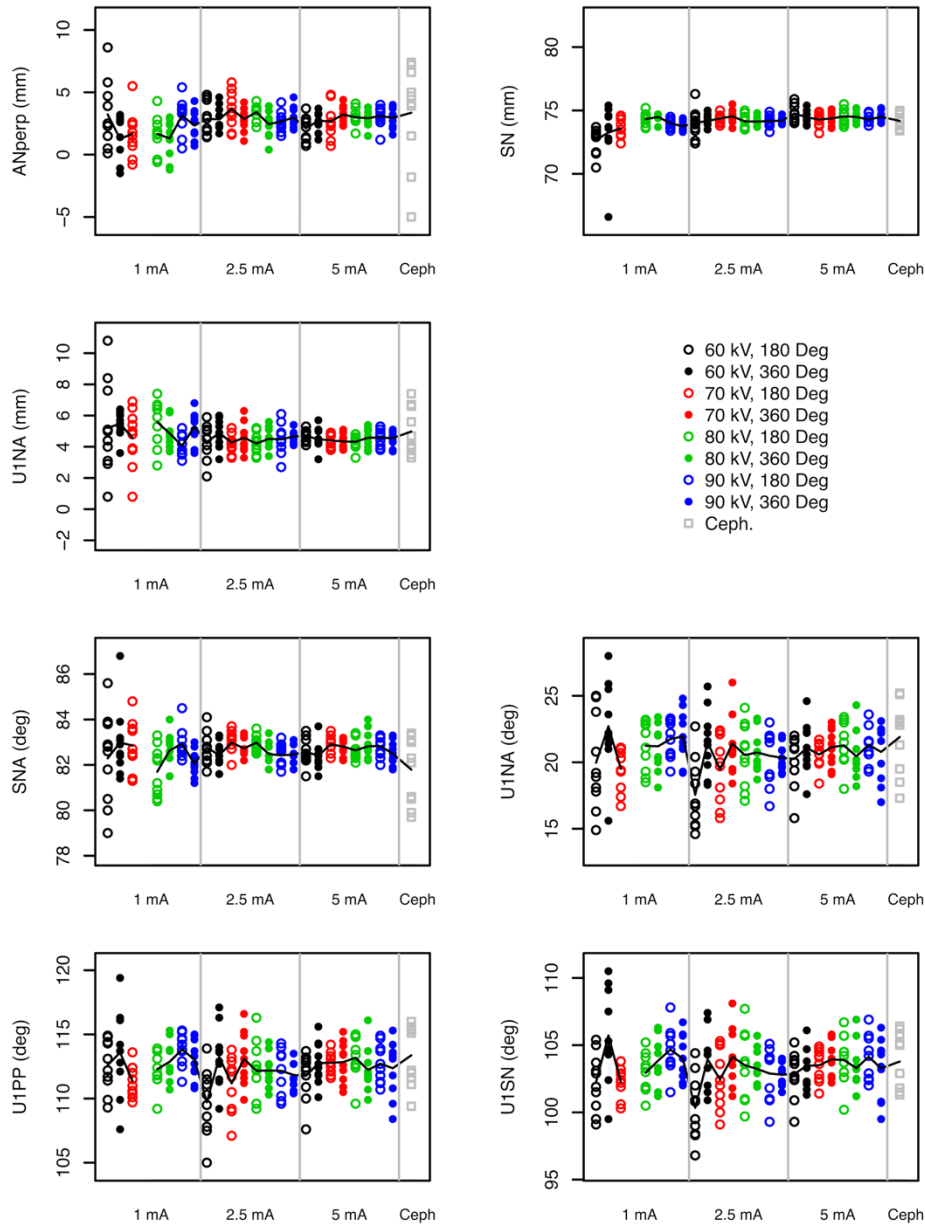


Figure 5. Graphic representation of the measurements and their means organized by mA settings. Each colored point is a cephalometric measurement and the black line connects the means of these measurements. If the points are spread apart it shows that there is more variation in measurements for that setting (ie. more disagreements between examiners). Note that variation decreases from 1mA to 5mA for A-Nperp, U1-NA (mm) and SNA – the points lie closer together and the black line becomes straighter as the mA increases.

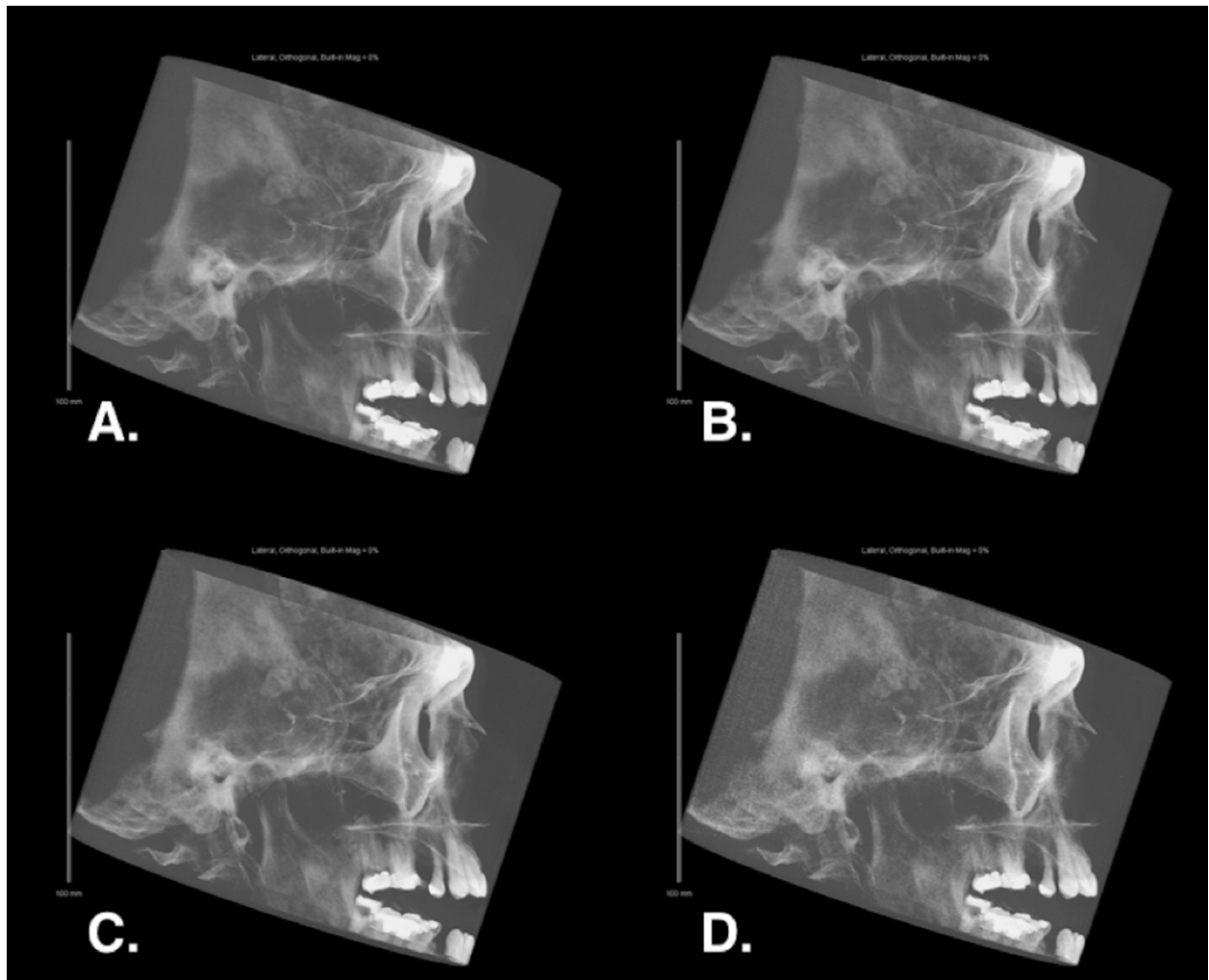


Figure 6. Images taken at: **A.** 5mA, 90kV, 360°, **B.** 5mA, 80kV, 360°; **C.** 5mA, 70kV, 360°; **D.** 5mA, 60kV, 360°

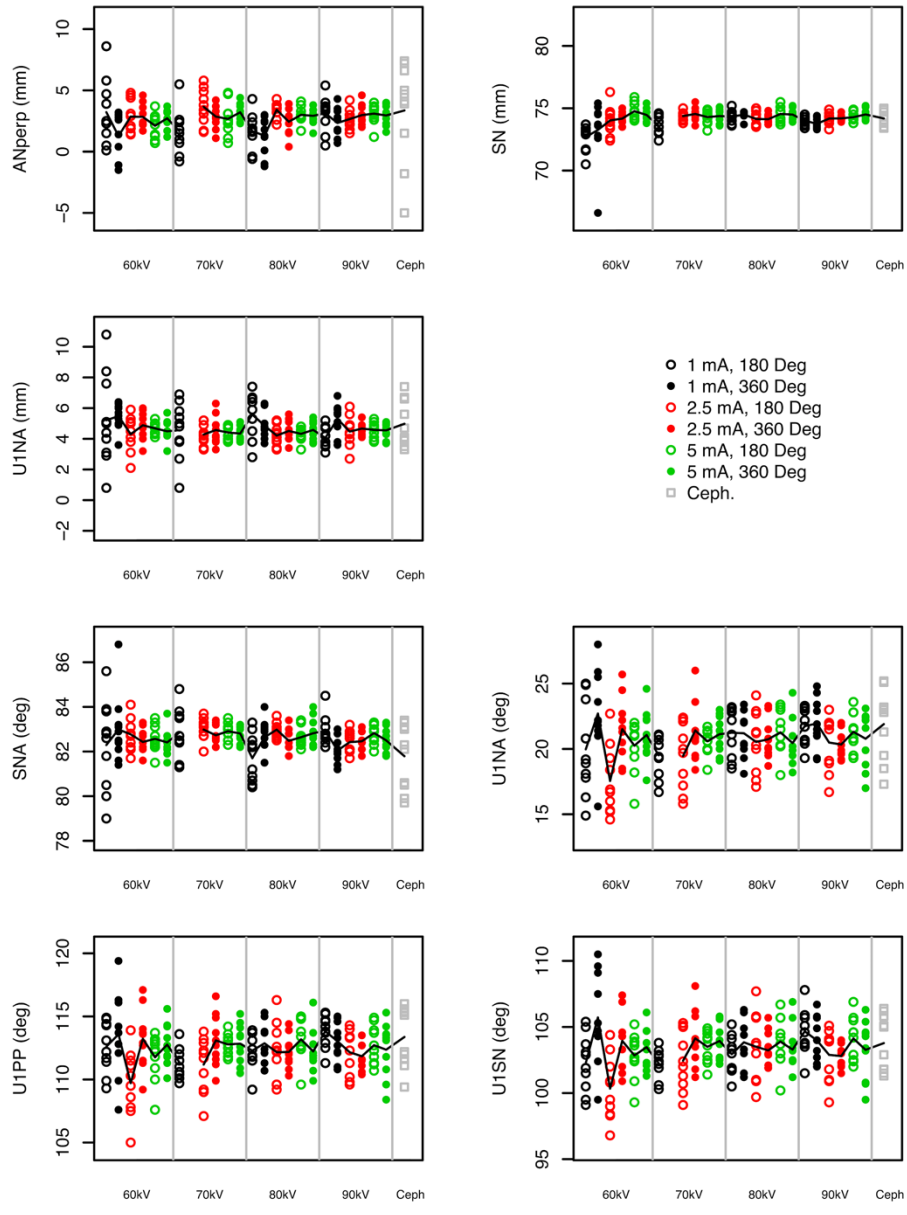


Figure 7. Graphs with the measurements and their means organized by kV settings. Each colored point is a cephalometric measurement and the black line connects the means of these measurements. If the points are spread apart it shows that there is more variation in measurements for that setting (ie. more disagreements between examiners). Note that variation was greatest for 60kV and 1mA settings for A-Nperp, SN, U1-NA (mm), SNA - the points are more spread and the black line has a zigzag course in these areas of the graphs.

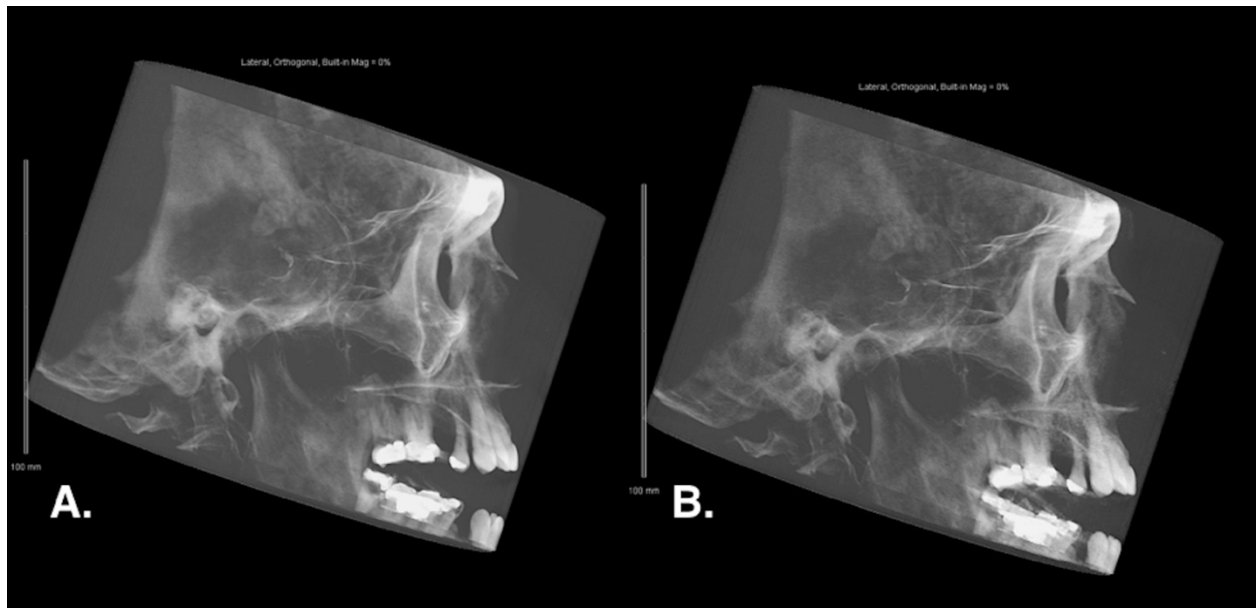


Figure 8. Images taken at: **A.** 5mA, 90kV, 360°; **B.** 5mA, 90kV, 180°

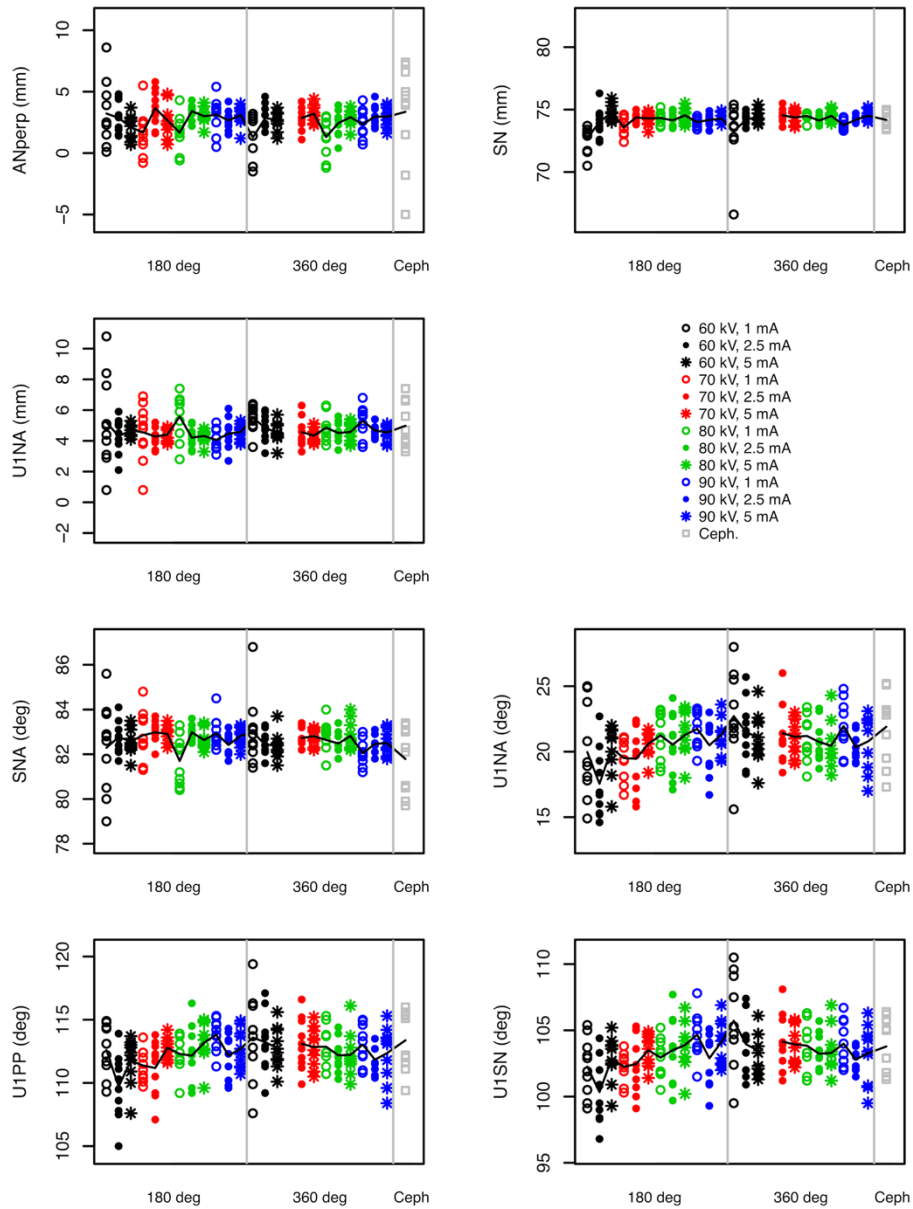


Figure 9. Graphs with all measurements, their means and trends organized by 180° and 360° exposure settings. Each colored point is a cephalometric measurement and the black line connects the means of these measurements. If the points are spread apart it shows that there is more variation of measurements for that setting (ie. more disagreements between examiners). Note that variation was greatest for the 1mA settings for most measurements - the points are more spread but the variation was similar when comparing 180° with 360° rotation.

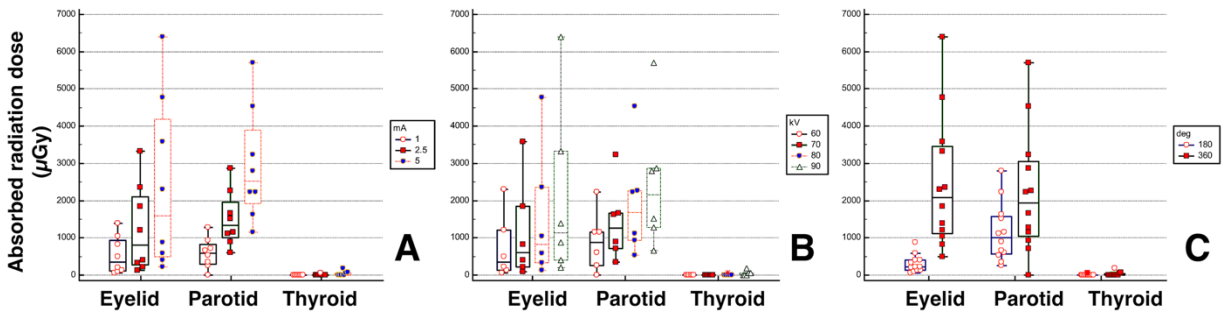


Figure 10. Radiation dose variation relative to: **A.** mA; **B.** kV, **C.** 360° vs. 180° rotation.

Boxplots with median, quartiles and whiskers for minimum and maximum values. The distribution for the boxplots is high because they include the variation of radiation doses from all the other modified settings (kV, mA, rotation).

DISCUSSION

In this study we evaluated the influence of changing mA, kV and arc of rotation on the reliability of cephalometric measurements made on lateral cephalograms derived from CBCT. By modifying the scanning parameters, the image quality was altered, but could maintain a diagnostic level of acceptance for our measurements, while radiation dose reduction was confirmed by the radiation dosimeters.

Previous publications by Pauwels et al. 2012 and Kwong et al. 2008 have shown that lowering mA still resulted in diagnostic images, however these images look less appealing than the ones produced with the manufacturer recommended settings.^{9,10} Kwong et al. used the CB Mercuray CBCT (Hitachi Medical Systems, Tokyo, Japan) to investigate the impact of modifying kV and mA and asked whether the images had sufficient diagnostic quality for a general screening (i.e. bone levels, caries, TMJ, sinuses, pathology). They concluded that

changing the kV setting did not impact the diagnostic quality of images when lowered from 120kV to 100kV. In their study, images taken at lowered mA settings (from 15mA to 10mA to 5mA) showed good diagnostic quality depending on the field of view (FOV) of the scan. In our study, the mA setting was decreased to an even lower level and it was found that decreasing from the recommended 5mA to 2.5mA produced images with similar measurement error for cephalometry. The 2.5mA images were grainier than the 5mA images, but this did not have a clinically relevant impact on the cephalometric diagnoses (see Fig. 4). Although some differences in measurement error between 5mA and 2.5mA were statistically significant, they were probably not clinically relevant. For example, a difference of 0.4° or 0.2mm does not have a real impact on a cephalometric diagnosis. Lowering the mA value from 5mA to 2.5mA still produced images that are reliable for cephalometric measurements. Further lowering the mA value to 1mA produced images with less reliable orthodontic cephalometric measurements. The 1mA images were of poor quality due to substantial image noise and they were therefore considered non-diagnostic.

Ganache et al.¹¹ investigated the impact of lowering kV on the diagnosis of apical root resorption (CS 9300 CBCT scanner, Carestream Health, Inc., Rochester, NY). They concluded that radiation dose was reduced and image quality was maintained while lowering from 90 to 60kV and keeping “moderate-to-high mA setting”. They increased from 5mA to 6.3mA and 15mA in their study in order to maintain image quality. Another study has also shown that lowering the kV setting can produce images diagnostic for TMJ and sinus evaluation.¹² Comparably, when we decreased from the recommended 90kV to 80kV, the images were similar and none of the cephalometric measurement errors were statistically significantly different. When lowering down to 70kV, one measurement had statistically increased error but the absolute

error was not considered clinically relevant. At 60kV the images became unreliable for almost all cephalometric measurements due to increased errors that were statistically significant different from the ones at 70kV, 80kV and 90kV (see Fig. 6).

Lennon et al.¹³ and Durack et al.¹⁴ investigated whether reducing the arc of rotation to 180° influences the ability to diagnose apical lesions for endodontic diagnosis. They concluded that 180° CBCT yielded similar accuracy in the detection of artificial bone lesions and advised the use of 180° scans in order to reduce radiation dose. Cook et al.¹⁵ investigated in a cadaver study the impact of shortening exposure time by using half rotation acquisitions on measurement of buccal bone height and thickness. They observed that results were similar when comparing short versus long scan times and they favored using the 180° instead of 360° arc of rotation for dose reduction unless a higher resolution was needed for a specific reason. Our study produced similar results in the sense that the CBCT images taken at 180° had a similar diagnostic value as 360° for cephalometric measurements. Although statistical significant differences were found in two of the seven measurements, there were no major clinical differences between 360° and 180° images when the two images were put side by side (see Fig. 8). Even if the 180° image contained slightly more noise, changing the degree of rotation to half had a negligible effect of diagnostic value. For example, in the current analyses, the error for the U1-NA distance was on average 0.34 mm more for 180° as opposed to 360° (respective means were 1.08mm and 0.74mm) which was statistically significant but not necessarily clinically relevant. Only if 0.34mm is considered important by the practitioner would it be worth using 360° instead of 180°. If one is taking a CBCT scan with the purpose of assessing fenestrations or the level of crestal bone for example, then the exposure settings might need to be maintained to the manufacturer recommended settings in order to keep a high enough quality for diagnosis. More and more evidence supports

that half rotation CBCT could be as diagnostic as a full rotation CBCT depending of the imaging task, while having the advantage of a radiation dose reduction of 45%.

As the lens of the eye, the thyroid and salivary glands are among the most vulnerable organs in the cranio-facial region we should take into account that the radiation is only being applied to a limited area of the body even if it is usually reported as a whole body radiation dose (effective dose).¹⁶ The doses we recorded were highest for the parotid and eyelid and were confirmed to decrease greatly when using lowered settings. Since we were not able to include the entire mandible in the scan, the thyroid gland absorbed doses were low in our study as only small scattered radiation was recorded. Diagnostic radiation effects are probabilistic in nature and it is impossible to make a difference between “safe” and “unsafe” radiation levels. It is considered therefore that any amount of additional radiation is associated with a finite cumulative risk and this risk can be decreased by lowering the mA or kV or by adjusting the CBCT arc of rotation to 180° instead of 360°.

In the present study, we used only one CBCT machine and therefore our results cannot be fully generalized to all CBCT scanners. A major concern with CBCT machines is that they are not all uniform and every manufacturer decides autonomously on the kV, mA and arc of rotation settings. Our study emphasizes the need to conduct similar studies on all CBCT scanners that are available on the market in order to establish dose optimization protocols. The manufacturer’s settings do not necessarily guarantee the lowest radiation dose with the best risk/benefit ratio for the patient.

Another limitation of our study is that we used one elderly male human cadaver (82 years old) which is not representative for the average adolescent patient due to altered bone density and overall size. However, it is neither feasible to find an adolescent cadaver nor ethically

acceptable to apply a similar research protocol on live patients. We were not able to conduct the study on more than one cadaver either. Because the cadaver was elderly and large, its bone structure was overall less clear than what would be expected of a clinical image. This subject was more sensitive to image quality deterioration than under typical clinical circumstances. Additionally, the cadaver was fixed in embalming fluid and it is uncertain exactly how that might affect the image quality. Another limitation is that the dosimeters were exposed only once, which is not the case in other studies where a phantom is used instead of a cadaver. Therefore, the recorded radiation doses might have been under- or overestimated, however the changes in dose due to altered exposure settings can be considered reliable and realistic. Multiple exposures at the same settings were not possible in this study, as this would have increased the experimental time of the study and affected the stability of the cadaver. For practical reasons, the cadaver was exposed 24 times in a single session.

Despite these limitations, it is clear that a lower radiation dose does not always deteriorate the diagnostic quality of an image. These findings draw attention to the potential of developing customized exposure protocols that decreases radiation dose while maintaining the diagnostic value of images.

CONCLUSIONS

1. The present study demonstrates the concept of reducing CBCT radiation dose by lowering the exposure settings. The quality image is expected to decrease but the diagnostic value may be maintained even if using a lower dose protocol. Further research is recommended in order to determine how this concept can be generalized and applied to other CBCT machines.
2. Specifically, in the present study the mA setting was lowered from 5mA to 2.5mA and still maintained sufficient image quality for cephalometric measurements. This setting would reduce radiation dose with 50%.
3. The kV setting was lowered from 90kV to 80kV with 20-25% radiation dose reduction with similar diagnostic value, and could possibly be lowered to 70kV with images maintaining sufficient quality for reliable cephalometric measurements.
4. Taking a CBCT scan at 180° instead of 360° did not alter the diagnostic quality of the image for cephalometric interpretation. A half rotation CBCT reduces the radiation dose burden on patients by 45%.
5. Lowering the exposure settings to 1mA or 60 kV from the manufacturer recommendation for the Accuitomo® 170 CBCT machine (90kV, 5mA, 360°) yields images of poor diagnostic quality that are unreliable for cephalometric measurements.

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Appendix:

Definitions of cephalometric landmarks.

Sella: center of the pituitary fossa (Sella Turcica) of the sphenoid bone

Nasion: most anterior point of the naso-frontal suture

Porion: most superior point of the external auditory meatus

Orbitale: the most inferior point of the external border of the orbital cavity, using the most prominent orbital border

ANS: Anterior nasal spine

PNS: Posterior nasal spine

A-point: deepest point along the outline of the curve of the maxilla, between anterior nasal spine and dento-alveolar process

UI incisal tip: maxillary incisor tip, using most prominent incisor.

UI root tip: maxillary incisor root tip

Definitions of cephalometric measurements

A-N perpendicular (mm): distance between A-point and a perpendicular line through N-point

S-N line (mm): length of line connecting Sella and Nasion

UI-NA(mm): distance between labial surface of maxillary incisor and Nasion-A point line

UI-NA (degrees): value of angle formed by maxillary incisor axis with Nasion-A point line

SNA (degrees): value of angle formed by the three points Sella, Nasion, A-point

UI-PP (degrees): value of angle formed by maxillary incisor axis with palatal plane (line between ANS and PNS)

UI-SN (degrees): value of angle formed by maxillary incisor axis with S-N line