Original Article

Distortion and Magnification of Four Digital Cephalometric Units

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ABSTRACT

Objectives: To assess the validity of using the calibration ruler for correcting magnification of linear measurements and to explore and compare the vertical and horizontal magnification of four digital cephalometric units. **Methods:** An acrylic box was imaged at seven sagittal positions using four digital cephalometric units: Orthopantomograph OC100, Orthopantomograph OC200, Sirona Orthophos CD, and Sirona Orthophos DS. The true linear lengths of the phantom, corrected, and uncorrected linear lengths on the images were measured and compared. The validity of measurements using the calibration ruler was assessed. The magnification values and distortion indices were calculated and compared among the four cephalometric units. **Results:** For linear measurements on the mid-sagittal plane and averaged linear measurements on bilateral symmetric sagittal planes, the bias 1.96 STD of the calibration ruler ranged from 1% to 2% for the four cephalometric testing units. For linear measurements on the single lateral sagittal plane, the bias 1.96 STD ranged from 3% to 6%. The vertical scanning charge-coupled device cephalometric unit produced the greatest distortion, ranging from 1.029 to 0.964. **Conclusion:** The metal millimeter calibration ruler is an accurate reference for linear measurement magnification correction. Because of unpredictability and machine specificity, the magnification and distortion of a cephalometric unit should be calibrated for the estimation of cephalometric measurement error.

Keywords: *Cephalometric measurement, distortion, magnification*

Introduction

Since the invention of the Broadbent-Bolton cephalometer in 1931,[1] lateral cephalometric radiographs have become virtually indispensable to orthodontists in orthodontic treatment. A cephalometric film is a relatively standardized representation of the human skull which allows precise measurement and comparison of oral and craniofacial structures, so as to predict and evaluate growth and maturation, make an orthodontic diagnosis and a treatment plan, and assess orthodontic treatment outcomes.[1,2] Cephalometric measurements are performed using a two-dimensional image of a three-dimensional object. Ideally, for a lateral cephalometric radiograph, measurements should be performed with all anatomical landmarks projected onto the mid-sagittal plane of the patient. However, because of the divergent pattern of the x-ray beam and the distance between the object and image-receptor, distortion always exists as an inherent limitation.[3]

Two types of distortion have been identified, namely, size distortion (magnification) and shape distortion.[4] Size distortion refers to an accurate and proportional expansion of the image, which only influences linear measurements instead of angular measurements. Shape distortion refers to an inaccurate and unequal-ratio enlargement, resulting in distortion errors both in linear and angular measurements.[5,6] Because of the variance in x-ray geometry shapes among different cephalometric systems,

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magnification and distortion may be machine specific. Dibbets JM and Nolte K studied the effect of radiographic magnification in five longitudinal cephalometric databases.[5] Their results showed that cephalometric tracing was corrected to the natural size in the Groningen and London study and magnified 6% in the Cleveland and Philadelphia and 12.9% in the Ann Arbor studies. This indicated that the error inherent in magnification was too great to be ignored. Chadwick JW and Schulze RK compared the distortion and magnification of four cephalometric units. They reported the conventional cephalostat and Sirona orthophos DS systems produced the greatest magnification and distortion while the OC 100D and Kodak 8000C systems produced the least. The distortion indices varied from ±1% to ±5%[7,8] among the four cephalometric units.

When comparing cephalometric data from different sources in a multi-center study, it is of great significance to make an accurate magnification correction for linear distance. At present, most cephalostats have a metal millimeter calibration ruler attached to the nosepiece. The ruler is generally designed for linear measurement correction on digital imaging.[6,9] Through identifying two endpoints on the ruler, it is convenient to correct all the linear values according to the ratio of the pixel distance to the actual length of the ruler. However, with the calibration ruler being positioned vertically, it is unclear whether linear measurements in the horizontal orientation could be correct when obtained using a single ruler. For tracing bilateral structures, some researchers took an average as a presentation[10,11] and others traced the image of the single side near the receptor, which was less magnified and could be the left side[12] or the right side.[8] For the two methods mentioned above, it is not fully known to what extent the estimation affects the accuracy of cephalometric measurements. Furthermore, since cone beam computed tomography (CBCT) was first introduced in dentistry in 1998,[13] recently, it has been used widely in orthodontics for clinical and research purposes. Many studies compared the measurements from three-dimensional reconstructed and synthesized lateral cephalograms obtained using CBCT with those from two-dimensional images obtained from conventional lateral cephalometric radiographs.[14-16] However, it remains unclear whether we should use the averaged image of both sides or the unilateral image less magnified in conventional cephalograms.

The current study aimed to assess the validity of the calibration ruler for correcting the magnification of structures on the mid-sagittal plane and bilateral structures outside the mid-sagittal plane, and also to explore and compare the vertical and horizontal magnification of four digital cephalometric units.

Materials and Methods

Radiographic phantom and imaging

A radiographic phantom was designed and prepared for this study. The phantom was created using a custom-designed acrylic box with the following dimensions: inside diameter, 25 cm in height, 25 cm in width, and 25 cm in depth (thickness of the walls of the acrylic box: 0.5 cm). 7 positions were designed to simulate important bilateral anatomical structures. Position 4 in the middle was considered as the mid-sagittal plane of the skull. Positions 3 and 5 were 2.5 cm away from the mid-sagittal plane, corresponding to molar sagittal planes; positions 2 and 6 were 4.5 cm away from the mid-sagittal plane corresponding to the mandibular sagittal planes; positions 1 and 7 were 6.0 cm away from the mid-sagittal plane, corresponding to the condylar sagittal planes. Position 1 was located closest to the image receptor, whereas position 7 was located closest to the x-ray source [Figure 1a and b]. A single sheet of acrylic, measuring 25 cm in height by 25 cm in width by 0.5 cm in thickness, was embedded with one steel ball of 0.5 cm diameter placed in the center and 48 steel balls of 1.58 mm in diameter placed on four concentric circles surrounding the center. The four concentric circles were 3, 6, 9, and 12 cm in diameter. The single acrylic sheet was designed with 2 sliding pieces (1.0 cm × 1.0 cm × 0.5 cm) on the outside of both top angles in order to make the sheet plumb and running along the central line of the x-ray beam, parallel from one position to another [Figure 1c].

4 cephalometric units were used in this study: Orthopantomograph OC100 (Instrumentarium Dental, Nahkelantie, Finland), Orthopantomograph OC200 (Instrumentarium Dental, Nahkelantie, Finland), Sirona Orthophos CD with multi-pulse Cephalograph (Sirona, Munich, Germany), and the vertically scanning Sirona Orthophos DS (Sirona, Munich, Germany). The acrylic box was mounted on a camera tripod (VCT-80AV; Sony, Tokyo, Japan). The tripod head was placed horizontally so that the base of the box was placed parallel to the floor, and the lateral walls of the box were placed vertically. With properly fixed inter-ear-rod distance, the ear rods were in alignment with the central point of the acrylic sheet. The acrylic sheet was placed parallel to the film to ensure a normal incidence of the x-ray beam. For each cephalometric unit, the acrylic sheet was placed at each position in the acrylic box for one projection, yielding 28 x-ray films in total [Figure 1d and e].

Measurements

3 orthodontic residents identified landmarks on 28 digital films and measured true distances of the acrylic phantom

by using a vernier caliper (0.01 mm). Distances on the digital films were measured using the customized software calibrated for pixels/mm. By identifying two endpoints on the calibration ruler, the magnified linear distances were corrected according to the ratio of pixel distance to the real length of the ruler. The measured distances, corrected and uncorrected, were recorded in millimeters.

As shown in Figure 2, the four points on the circle were defined and labeled clockwise from point A to point D. Six linear measurements on each concentric circle, AB, BC, CD, DA, AC, and BD, were recorded in millimeters. Different subscript values of point labels represented different diameters; for example, $AC_{9.0}$ referred to AC on the circle 9.0 cm in diameter.

The magnification value was calculated according to the following formula:

Magnification value = Radiographic length (mm)/True length (mm)

The distortion index was defined as the ratio of magnification values between the vertical direction and horizontal direction. $AC_{9.0}$ was regarded as the vertical linear measurement and $BD_{9.0}$ was regarded as the horizontal linear measurement. For each sagittal position, vertical ($AC_{9.0}$) and horizontal ($BD_{9.0}$) lengths were measured and the magnification values were computed separately. The linear distortion index was calculated as follows: Magnification value of $AC_{9.0}$/ Magnification value of $BD_{9.0}$. On the mid-sagittal plane (Position 4), four linear measurements (AB, BC, CD, and DA) for each concentric circle were measured and the magnification values were calculated.

Statistical analysis

All statistical analyses were performed using SPSS software (version 20.0; SPSS, IBM). An analysis of variance with S-N-K (Student Newman Keuls) testing was used to determine the differences between true distances and the linear measurements made on the images. Pearson correlation analysis was conducted to analyze the correlation relationship between magnification value and the subject-to-film distance. Graphs were generated using MATLAB (R2011b; MathWorks, USA), Visio (Microsoft Visio Premium 2010; Microsoft, Redmond, WA), and SPSS software.

Results

The true measured distances of the phantom and the uncorrected and corrected measured distances of $AC_{9.0}$ and $BD_{9.0}$ at each position on the image are shown in Table 1. The results of S-N-K testing showed that all the uncorrected measurements were significantly different from the true measured distances. Except for the $AC_{9.0}$

Table 1: Linear measurements of vertical length and horizontal length at each position (length: in millimeter)

Position	Distance	True in mm	OC 100		OC 200		Orthophos CD		Orthophos DS	
			Corrected in mm	Uncorrected in mm	Corrected in mm	Uncorrected in mm	Corrected in mm	Uncorrected in mm	Corrected in mm	Uncorrected in mm
1	$AC_{9.0}$	89.76±0.04	86.95±0.30†	99.20±0.35†	86.37±0.37†	98.88±0.42†	87.10±0.39†	97.87±0.44†	89.58±0.34^{NS}	98.41±0.37†
	$BD_{9.0}$	90.04±0.05	88.20±0.32†	100.51±0.37†	87.34±0.31†	100.01±0.35†	86.58±0.37†	97.54±0.42†	87.20±0.38†	95.94±0.42†
2	$AC_{9.0}$	89.76±0.04	87.63±0.33†	99.85±0.38†	87.50±0.33†	100.26±0.38†	87.56±0.32†	98.47±0.36†	89.41±0.41^{NS}	98.30±0.45†
	$BD_{9.0}$	90.04±0.05	88.43±0.38†	101.11±0.44†	88.75±0.25†	101.49±0.29†	87.22±0.37†	98.07±0.42†	87.89±0.43†	96.75±0.47†
3	$AC_{9.0}$	89.76±0.04	88.27±0.33†	100.80±0.38†	88.12±0.39†	101.01±0.44†	88.82±0.28†	99.96±0.32†	89.42±0.46^{NS}	98.35±0.50†
	$BD_{9.0}$	90.04±0.05	89.27±0.35*	102.10±0.40†	89.41±0.32*	102.32±0.36†	88.43±0.33†	99.55±0.38†	88.81±0.47†	97.67±0.52†
4	$AC_{9.0}$	89.76±0.04	89.54±0.25^{NS}	102.12±0.28†	89.54±0.31^{NS}	102.42±0.35†	89.59±0.38^{NS}	100.69±0.43†	89.51±0.35^{NS}	98.43±0.38†
	$BD_{9.0}$	90.04±0.05	90.23±0.31^{NS}	103.27±0.35†	90.30±0.40^{NS}	103.59±0.46†	89.77±0.29^{NS}	100.39±0.33†	90.08±0.39^{NS}	99.08±0.43†
5	$AC_{9.0}$	89.76±0.04	90.98±0.32†	103.85±0.36†	90.80±0.37†	104.04±0.42†	90.72±0.34†	102.15±0.39†	89.57±0.41^{NS}	98.41±0.45†
	$BD_{9.0}$	90.04±0.05	92.09±0.35†	105.16±0.40†	92.13±0.33†	105.41±0.38†	91.09±0.41*	101.54±0.47†	91.27±0.35†	100.35±0.38†
6	$AC_{9.0}$	89.76±0.04	92.19±0.30†	105.07±0.35†	91.84±0.39†	105.01±0.45†	92.05±0.31†	103.51±0.35†	89.34±0.34*	98.36±0.37†
	$BD_{9.0}$	90.04±0.05	93.25±0.37†	106.46±0.42†	92.62±0.22†	106.07±0.25†	91.79±0.25†	103.18±0.29†	92.20±0.38†	101.40±0.42†
7	$AC_{9.0}$	89.76±0.04	92.37±0.39†	105.41±0.44†	92.53±0.33†	105.94±0.38†	92.39±0.32†	103.88±0.37†	89.59±0.51^{NS}	98.45±0.46†
	$BD_{9.0}$	90.04±0.05	93.40±0.32†	106.59±0.37†	93.55±0.28†	107.09±0.32†	91.71±0.18†	103.28±0.26†	93.17±0.43†	102.43±0.47†

OC100, Orthopantomograph OC100 (Instrumentarium Dental, Nahkelantie, Finland); OC200, Orthopantomograph OC200 (Instrumentarium Dental, Nahkelantie, Finland); Orthophos CD, Sirona Orthophos CD with multi-pulse Cephalograph (Sirona, Munich, Germany); Orthophos DS, Sirona Orthophos DS (Sirona, Munich, Germany). $^{*}P<0.05$. $^{\dagger}P<0.001$

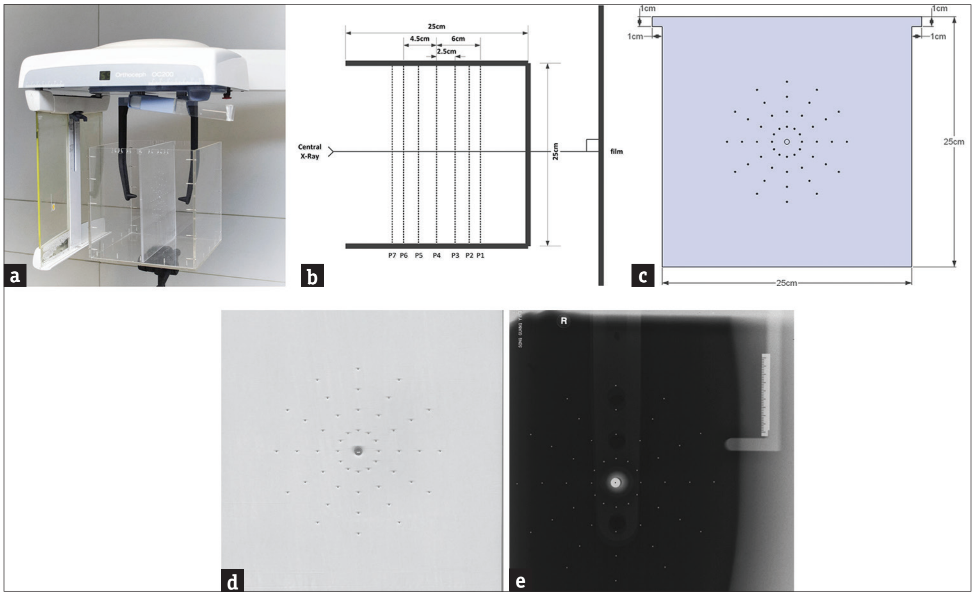

Figure 1: (a) Acrylic box phantom mounted in the OC100 cephalostat. (b) Position 1 to position 7. (c) Acrylic sheet with two sliding pieces. (d) Scan of acrylic box phantom. (e) Image of acrylic box phantom

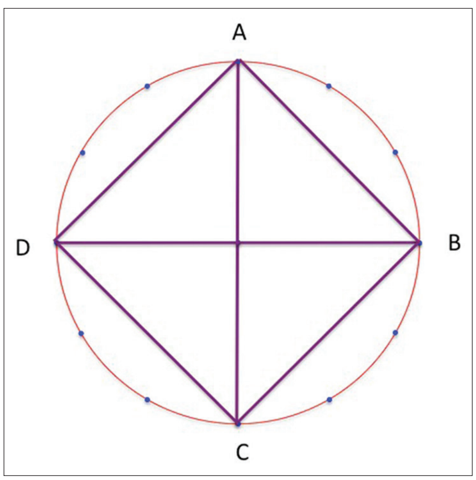

Figure 2: Points and linear measurements on the circle

of Orthophos DS, all the corrected measurements outside the mid-sagittal plane were also significantly different from the true measured distances. The corrected measurements at position 4 (mid-sagittal plane) were comparable to the true measured distances.

At position 4, the true lengths of the phantom and corrected and uncorrected measured lengths of AB, BC, CD, and DA on each concentric circle are listed in Table 2. All the uncorrected measurements were significantly larger than the true measured distances. There were statistically significant differences between some corrected measurements on the images obtained with Orthophos CD and Orthophos DS compared with the true measured distances. All the corrected measured distances on the images obtained with OC 100 and OC 200 were comparable to the true measured distances.

In order to assess the validity of the calibration ruler of each cephalometric system, Bland-Altman plots were created to show the agreement between corrected measured distances and true measured distances in Figures 3-5. The Bland-Altman plots show the difference against the average measurements for a particular cephalometric method and physical method. The average difference was calculated as the ratio of two measurements to quantify the bias. The farther away from 1, the greater the amount of bias, indicating that the corrected measured distances were different from the true measurements. The upper and lower lines on the plots show ±1.96 STD (standard deviation) respectively.

Figure 3 illustrates the chord measurements on the mid-sagittal plane. The 1.96 STDs of OC 100, OC 200, and Orthophos CD were about 1%, while that of Orthophos DS was about 2%. Figure 4 shows the measurements of $AC_{9.0}$ and $BD_{9.0}$ on each unilateral sagittal plane. The 1.96 STDs of the four cephalometric systems ranged from 3% to 6%, showing obvious distortion. The average measurements of $AC_{9.0}$ and $BD_{9.0}$ on the bilateral sagittal planes are graphically demonstrated in Figure 5. The 1.96 STDs of the four cephalometric systems were all less than 1%.

Magnification values of each position in Figure 6 were calculated as the ratios of uncorrected measured distances to the true measured distances from Table 1, and then correlated with the distance from each position to the mid-sagittal plane. All the magnification values increased linearly from position 1 to position 7 ($P < 0.05$), except that of the vertical length of Orthophos DS ($P > 0.05$), which was almost a constant value of 1.096.

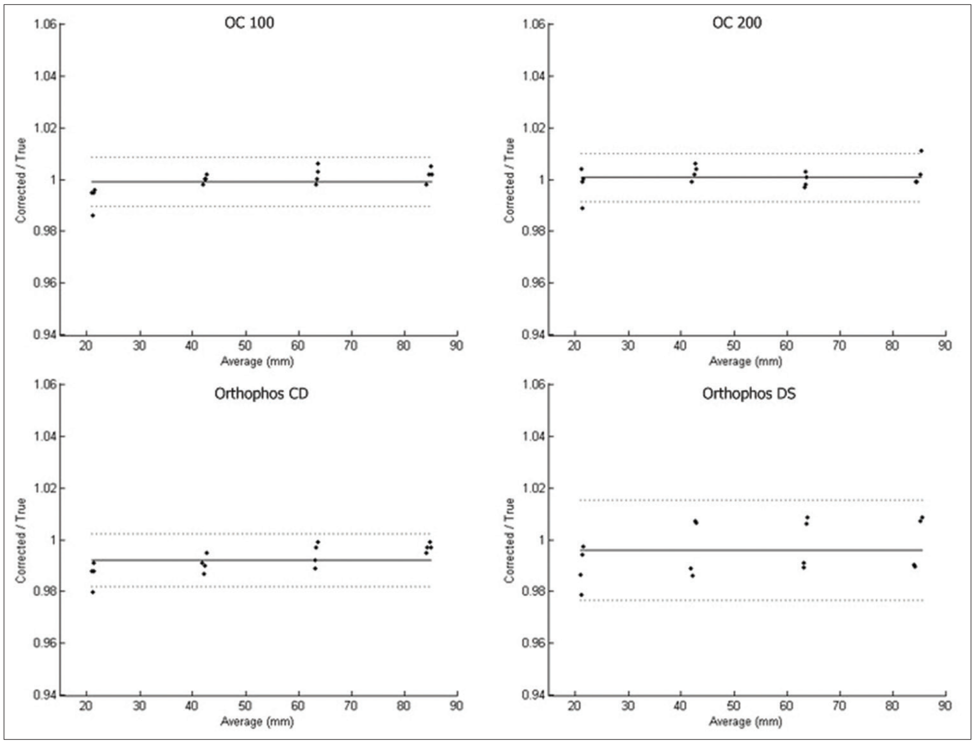

Figure 3: Bland–Altman plots of chord measurements on the mid-sagittal plane (corrected measured distances vs. true measured distances of AB, BC, CD, and DA on four concentric circles)

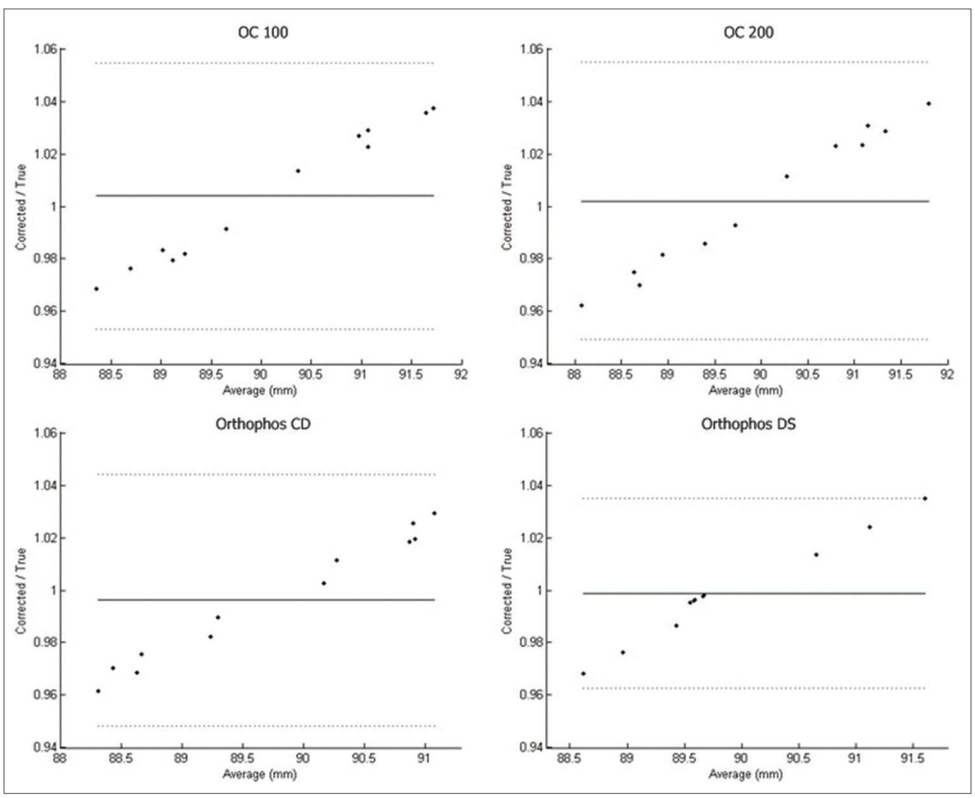

Figure 4: Bland–Altman plots of measurements on the unilateral sagittal plane (corrected measured distances vs. true measured distances of AC9.0 and BD9.0)

The distortion indices were calculated as ratios of vertical magnification values to horizontal magnification values. Figure 7 shows that at each position, the distortion indices are stable and close to 1.00 for OC100, OC200,

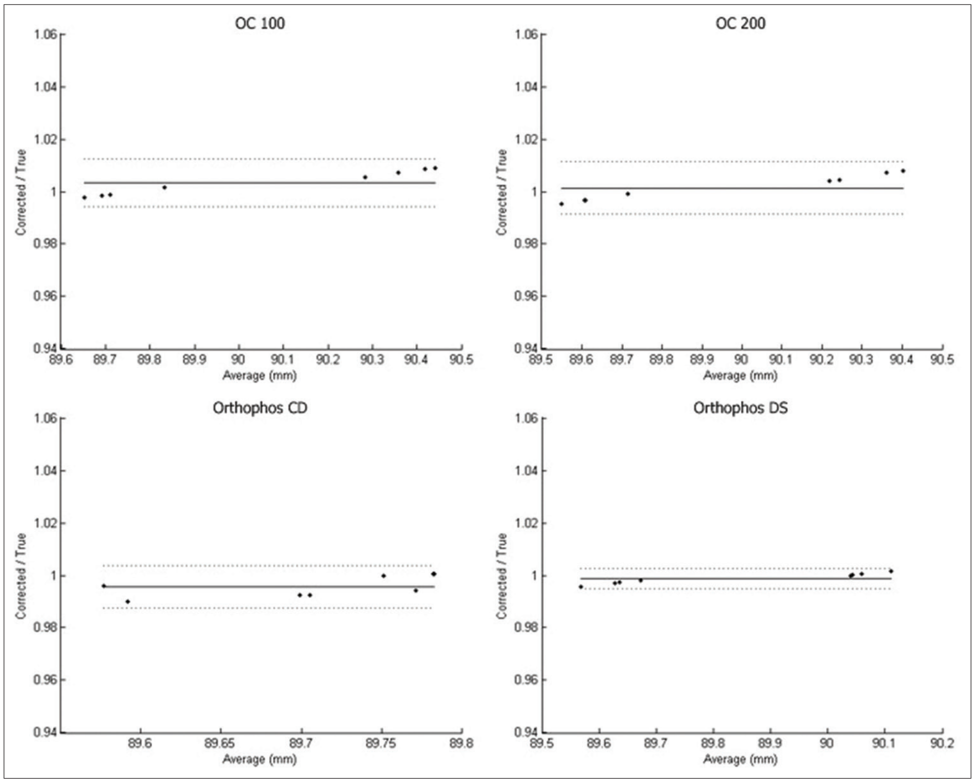

Figure 5: Bland–Altman plots of average measurements on bilateral sagittal planes (corrected averaged measurements of position 1 and position 7, position 2 and position 6, and position 3 and position 5 vs. the true measured distances of AC9.0 and BD9.0)

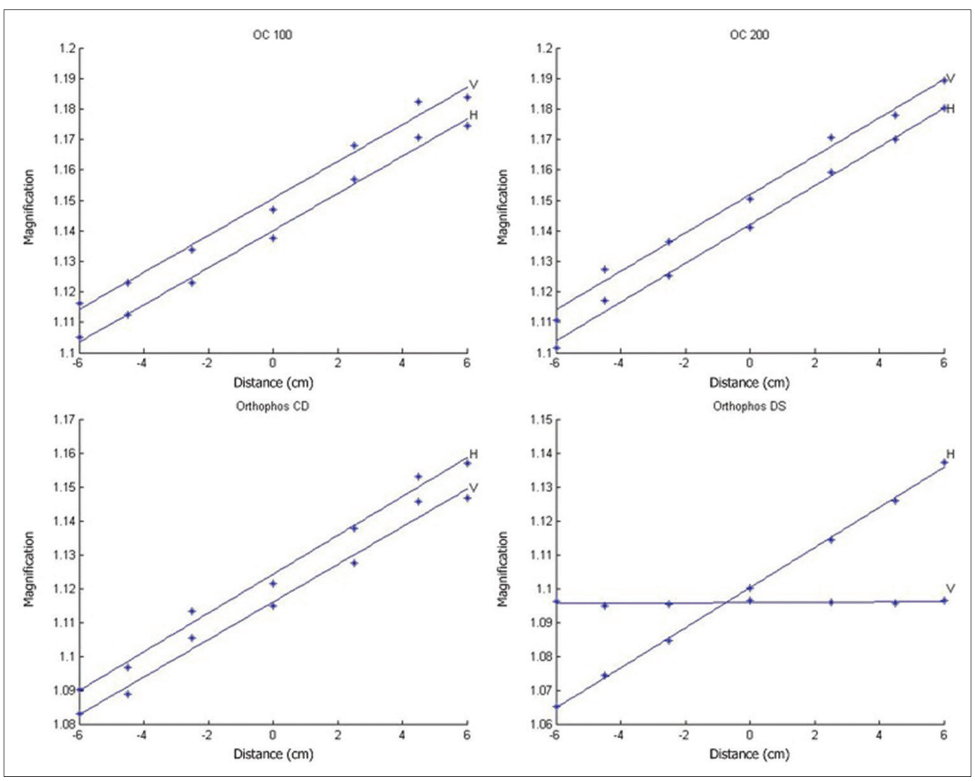

Figure 6: Scatterplot comparing the association between the magnification values of AC9.0 (V)/BD9.0 (H) and positions (x: distance from each position to mid-sagittal plane, y: magnification value of vertical and horizontal linear measurement. Pearson correlation: rOC100V = 0.997**, rOC200H = 0.994**; rOC200V = 0.998**, rOC200H = 0.996**; rOrthophosCDV = 0.996**, rOrthophosCDV = 0.993**; rOrthophosDSV = 0.425NS, rOrthophosDSV = 0.999**)

Table 2: Linear measurements of chord length of different concentric circles on mid-sagittal plane (length: in millimeter)

Circles	Length	True in mm	OC 100		OC 200		Orthophos CD		Orthophos DS	
			Corrected in mm	Uncorrected in mm	Corrected in mm	Uncorrected in mm	Corrected in mm	Uncorrected in mm	Corrected in mm	Uncorrected in mm
3.0 cm in Diameter	$AB_{3.0}$	21.35±0.04	21.05±0.37^{NS}	24.13±0.42†	21.11±0.31^{NS}	24.20±0.36†	20.93±0.30^{NS}	23.66±0.34†	20.90±0.42*	23.05±0.45†
	$BC_{3.0}$	21.44±0.04	21.36±0.34^{NS}	24.38±0.39†	21.44±0.41^{NS}	24.39±0.47†	21.25±0.36^{NS}	23.95±0.41†	21.38±0.37^{NS}	23.64±0.41†
	$CD_{3.0}$	21.02±0.07	20.92±0.35^{NS}	24.04±0.40†	21.11±0.30^{NS}	24.06±0.34†	20.78±0.27^{NS}	23.47±0.31†	20.73±0.34^{NS}	22.87±0.38†
	$DA_{3.0}$	21.34±0.05	21.23±0.37^{NS}	24.28±0.42†	21.31±0.37^{NS}	24.33±0.42†	21.09±0.39^{NS}	23.75±0.44†	21.22±0.40^{NS}	23.48±0.44†
6.0 cm in Diameter	$AB_{6.0}$	42.00±0.12	41.90±0.36^{NS}	47.96±0.41†	41.97±0.31^{NS}	48.04±0.36†	41.63±0.38^{NS}	46.89±0.43†	41.54±0.31*	45.65±0.34†
	$BC_{6.0}$	42.70±0.06	42.78±0.34^{NS}	48.85±0.39†	42.87±0.40^{NS}	48.82±0.46†	42.50±0.41^{NS}	47.85±0.46†	42.97±0.40^{NS}	47.31±0.44†
	$CD_{6.0}$	42.41±0.07	42.40±0.38^{NS}	48.43±0.43†	42.48±0.31^{NS}	48.46±0.36†	41.88±0.36^{NS}	47.18±0.41†	41.83±0.39*	46.15±0.43†
	$DA_{6.0}$	42.53±0.10	42.53±0.43^{NS}	48.71±0.49†	42.76±0.36^{NS}	48.75±0.41†	42.11±0.29^{NS}	47.57±0.33†	42.83±0.43^{NS}	47.10±0.48†
9.0 cm in Diameter	$AB_{9.0}$	63.48±0.06	63.38±0.31^{NS}	72.36±0.35†	63.28±0.39^{NS}	72.46±0.45†	62.96±0.38*	70.78±0.43†	62.91±0.38*	69.13±0.42†
	$BC_{9.0}$	63.66±0.11	63.82±0.35^{NS}	73.00±0.40†	63.75±0.33^{NS}	73.05±0.38†	63.60±0.40^{NS}	71.55±0.46†	64.01±0.31^{NS}	70.70±0.34†
	$CD_{9.0}$	63.60±0.11	63.57±0.30^{NS}	72.56±0.34†	63.47±0.39^{NS}	72.64±0.45†	62.89±0.33*	70.83±0.37†	62.92±0.39*	69.16±0.43†
	$DA_{9.0}$	63.53±0.06	63.89±0.37^{NS}	72.85±0.42†	63.69±0.40^{NS}	72.89±0.46†	63.36±0.41^{NS}	71.20±0.47†	63.93±0.35^{NS}	70.33±0.39†
12.0 cm in Diameter	$AB_{12.0}$	84.38±0.06	84.24±0.36^{NS}	96.33±0.41†	84.33±0.39^{NS}	96.48±0.45†	83.98±0.37^{NS}	94.45±0.42†	83.57±0.42†	92.11±0.46†
	$BC_{12.0}$	85.22±0.10	85.37±0.42^{NS}	97.70±0.48†	85.43±0.37^{NS}	97.66±0.43†	85.01±0.33^{NS}	95.77±0.37†	85.94±0.33 *	94.43±0.37†
	$CD_{12.0}$	84.59±0.08	84.74±0.27^{NS}	96.74±0.31†	84.51±0.30^{NS}	96.82±0.34†	84.36±0.33^{NS}	94.32±0.38†	83.72±0.27†	92.03±0.30†
	$DA_{12.0}$	84.91±0.04	85.07±0.39^{NS}	97.66±0.44†	84.94±0.37^{NS}	98.04±0.42†	84.80±0.38^{NS}	95.35±0.43†	85.52±0.31*	94.02±0.34†

OC100, Orthopantomograph OC100 (Instrumentarium Dental, Nahkelantie, Finland); OC200, Orthopantomograph OC200 (Instrumentarium Dental, Nahkelantie, Finland); Orthophos CD, Sirona Orthophos CD with multi-pulse Cephalograph (Sirona, Munich, Germany); Orthophos DS, Sirona Orthophos DS (Sirona, Munich, Germany). *P<0.05. $^{\dagger}P$<0.001

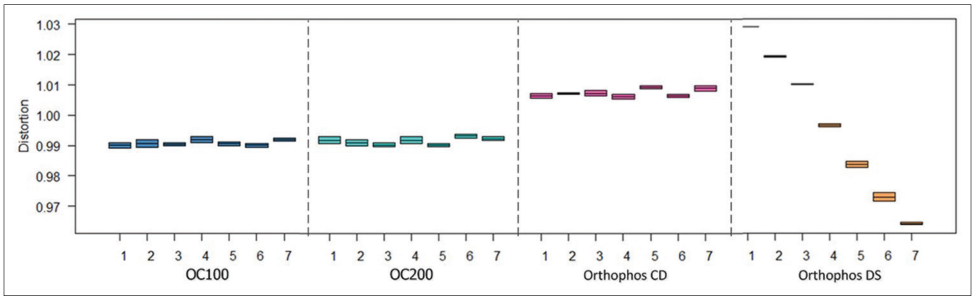

Figure 7: Distortion indices (H/V) of seven positions for four cephalometric systems

and Orthophos CD. However, for Orthophos DS, from position 1 to position 7, the distortion indices vary from 1.029 to 0.964, showing a significant linear correlation between the distortion index and the distance from each position to the mid-sagittal plane ($P < 0.05$).

Discussion

Distortion of cephalometric images has been discussed since the 1960s. Eliasson S and Ahlqvist J discussed in their serial basic mathematical studies that distortion could be caused by misalignment between the x-ray source, the cephalostat, the film, and the object. Their works provided a mathematical theoretical foundation for the explanation of image shape distortion.[17,18] Gron P, Yoon YJ, and Malkoc S reported the distortion errors introduced into linear and angular measurements on cephalometric films by the patient's head rotation.[19-21] Moreover, distortion is unavoidable for bilateral structures outside the mid-sagittal plane. Several studies focused on the distorted and non-superimposable images of bilateral symmetrical anatomical structure caused by differences in magnification.[22-24] Bergersen EO reported that for two lateral structures 12 cm apart, and the magnification difference was about 7%.[23] In our study, this magnification difference for two sagittal planes 12 cm apart was machine-specific: the average values for the Orthopantomograph OC100, Orthopantomograph OC200, Sirona Orthophos CD, and Sirona Orthophos DS were 6.8%, 7.9%, 6.5%, and 3.6%, respectively.

Furthermore, image distortion could also be influenced by x-ray beam geometry. After originating from the x-ray source in the tube, the x-ray beam travels in a divergent pattern with the field size limited by a collimator consisting of adjustable lead attenuators or shutter. The collimator and shutter control the size of the x-ray beam by absorbing peripheral x-rays. Among the four cephalometric systems used in this study, the Orthopantomograph OC100, the Orthopantomograph OC200, and the Sirona Orthophos CD were operated with a traditional divergent pattern of x-ray beams. For the Sirona Orthophos DS, with a fan-shaped x-ray beam coupled to a linear charge-coupled device (CCD) sensor array and x-ray beam collimator, the three parts scanned the object linearly in a vertical direction during image acquisition. Because of its special x-ray beam geometry, we expected the system to produce greater distortion error than the other three systems.

In previous studies, the magnification value could be calculated using the formula of proportion introduced by Adams JW in the 1940s, which specified that the distance from the x-ray source to the image-receptor/distance of the x-ray source to the patient's mid-sagittal plane = size of image/size of the object.[25] At present, a calibration ruler is used routinely to correct the magnification of cephalometric measurements, but its validity is seldom verified. There are several questions that merit further study as previously mentioned.

In the present study, to assess the validity of the calibration ruler, the corrected measured distances were compared with the true measured distances on the mid-sagittal plane and bilateral structures outside the mid-sagittal plane. The results of S-N-K testing listed in Table 1 show that at position 4, the corrected measured distances of $AC_{9.0}$ and $BD_{9.0}$ are both comparable to the true measured distances of $AC_{9.0}$ and $BD_{9.0}$. All the corrected measurements outside the mid-sagittal plane were statistically significantly different from the true measured distances, except for $AC_{9.0}$ on the images made with Orthophos DS. Table 2 shows that at position 4, the validity of the calibration ruler varied among the four cephalometric units. The corrected measured distances of AB, BC, CD, and DA on the images made with OC 100 and OC 200 were all comparable to the true measured distances. There were statistically significant differences between some corrected measurements on the images made with Orthophos CD and Orthophos DS compared with the true measured distances, whereas all the differences between corrected measurements and true measured distances were less than 1.00 mm.

Bland-Altman plots in Figure 3 illustrate the differences between the measurements of images made with each cephalometric unit and the true measurements at position 4. For OC 100, OC 200 and Orthophos CD, the bias was limited to ±1%. For Orthophos DS, the bias was about 2%. Bland-Altman plots in Figure 4 show the difference in every single position. The bias ±1.96 STD ranged from 3% to 6% among the four cephalometric units, demonstrating a large measurement error. Bland-Altman plots in Figure 5 show the difference between averaged measurements on bilateral sagittal planes with the true measurements. The biases of the four cephalometric systems were all less than 1%. The result showed that the four cephalometric units have a high degree of accuracy in predicting the true value of vertical and horizontal linear measurements, both on the mid-sagittal plane and the bilateral symmetric sagittal planes. Therefore, splitting the bilaterally separated images as an averaged representation on the patient's mid-sagittal plane is a valid approach. The error caused by this splitting could be ignored in clinical research.

However, to achieve maximum sharpness and reduce magnification, some practitioners choose to place the film cassette as close to the patient's head as possible and to trace the single image less magnified for bilateral structures. This tracing method is not recommended according to this study. The structures on the single side being traced were less magnified than the mid-sagittal structures as well as the ruler. Thus, if the ruler was used to correct the magnification, the sizes of these structures will be reduced. In contrast, on tracing with the splitting method, the magnification of this "average" will be almost the same as that of the ruler. Then the image could be corrected to its natural size. Consequently, if we intend to correct all linear measurements by using the radiopaque ruler, it is important to trace the average image for bilateral structures.

The magnification and distortion were measured and compared among the four cephalometric units. Figure 6 shows the vertical and horizontal magnifications at 7 positions for each cephalometric system. The magnification values increased approximately linearly along with an increase in the object-to-film distance, except for the vertical magnification of the scanning system, which showed a nearly constant value of 1.096. Vertical scanning during radiography might have changed the original symmetrical divergence of the x-ray beam. Figure 7 demonstrates the distortion between the vertical and horizontal axes at the seven positions for each cephalometric system. For 3 stationary cephalometric systems, the distortion indexes were stable and close to 1.00. The variations were all within 0.01. However, for the vertical scanning system, with the acrylic sheet moving further away from the mid-sagittal plane, the distortion errors increased linearly. The linear distortion errors varied from 1.029 to 0.964 for the vertical scanning CCD machine. The results were similar to the findings obtained by Chadwick JW and Schulze RK.[7,8]

In summary, when comparing cephalometric data from different sources, the metal millimeter calibration ruler attached to the nosepiece is an accurate reference for linear measurement magnification correction on digital imaging. The four cephalometric units showed a high degree of accuracy in predicting the true value of the distance on the mid-sagittal plane and the bilateral symmetric sagittal planes. In contrast, the measurement error for corrected linear distances on the unilateral sagittal plane varied from 3% to 6%. For the three stationary cephalometric units, the distortion indices between the vertical direction and horizontal direction are close to 1.00 on each sagittal plane. In contrast, for the vertical CCD scanning cephalometric unit, the distortion indices varied among different sagittal plane, showing larger distortion than the other three stationary digital cephalometric units.

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Conflicts of interest

There are no conflicts of interest.

Criteria for inclusion in the authors' list

1. Concept and design of study or acquisition of data or analysis and interpretation of data; 2. Drafting the article or revising it critically for important intellectual content; 3. Final approval of the version to be published.

Statement

I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed.

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