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Linear accuracy of cone-beam computed tomography and a 3-dimensional facial scanning system: An anthropomorphic phantom study

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ABSTRACT

Purpose: This study was conducted to evaluate the accuracy of linear measurements of 3-dimensional (3D) images generated by cone-beam computed tomography (CBCT) and facial scanning systems, and to assess the effect of scanning parameters, such as CBCT exposure settings, on image quality.
Materials and Methods: CBCT and facial scanning images of an anthropomorphic phantom showing 13 soft-tissue anatomical landmarks were used in the study. The distances between the anatomical landmarks on the phantom were measured to obtain a reference for evaluating the accuracy of the 3D facial soft-tissue images. The distances between the 3D image landmarks were measured using a 3D distance measurement tool. The effect of scanning parameters on CBCT image quality was evaluated by visually comparing images acquired under different exposure conditions, but at a constant threshold.
Results: Comparison of the repeated direct phantom and image-based measurements revealed good reproducibility. There were no significant differences between the direct phantom and image-based measurements of the CBCT surface volume-rendered images. Five of the 15 measurements of the 3D facial scans were found to be significantly different from their corresponding direct phantom measurements ($P < .05$). The quality of the CBCT surface volume-rendered images acquired at a constant threshold varied across different exposure conditions.
Conclusion: These results proved that existing 3D imaging techniques were satisfactorily accurate for clinical applications, and that optimizing the variables that affected image quality, such as the exposure parameters, was critical for image acquisition. ***(Imaging Sci Dent 2018; 48: 111-9)***

KEY WORDS: Imaging, Three-Dimensional; Dimensional Measurement Accuracy; Anthropometry; Cone-Beam Computed Tomography

Introduction

Making an accurate diagnosis is essential for adequate treatment planning and achieving successful treatment outcomes. The precise imaging of a patient's anatomical structures is a precondition for diagnosis, treatment planning, and evaluation of the outcomes of orthodontic treatment and orthognathic surgery.[1,2] Conventional cephalometric radiographs and 2-dimensional (2D) photographs have been useful tools for diagnosis, as well as treatment planning and assessment, in clinical orthodontics. However, the precision with which these tools can visualize complicated facial structures is limited.

Three-dimensional (3D) diagnosis and evaluation have become possible since the development of cone-beam computed tomography (CBCT) and facial scanners.[3,4] In particular, the application of CBCT in clinical orthodontics has become more common because of its advantages over conventional computed tomography (CT), such as cost-effectiveness, a low radiation dose, relatively fast scanning, and the compact size of the unit. Consequently,

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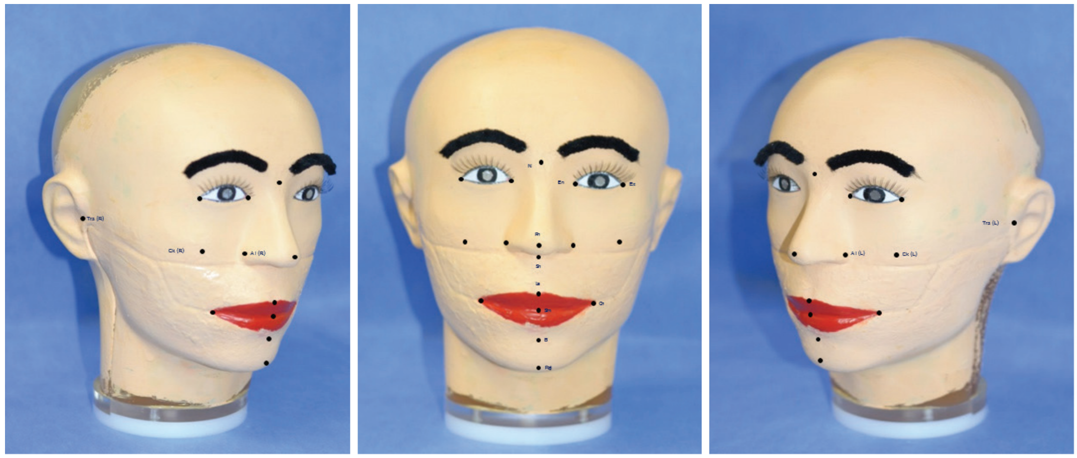

Fig. 1. Thirteen soft-tissue anatomic landmarks labeled on the anthropomorphic phantom, as described by Farkas.[13]

Table 1. Definition of craniofacial surface landmarks used in this study

Landmarks		Definition
Face	Sublabiale (B′)	The lower border of the lower lip or the upper border of the chin
	Tragion (Tra)	The notch on the upper margin of the tragus
	Cheek (Ck)	The intersecting point of lines connecting Ala-Tra and Ex-Ch
	Pogonion (Pog′)	The most anterior midpoint of the chin, located on the skin surface in front of the identical bony landmark of the mandible
Orbit	Endocanthion (En)	The point at the inner commissure of the eye fissure
	Exocanthion (Ex)	The point at the outer commissure of the eye fissure
Nose	Nasion (N)	The point in the midline of both the nasal root and the naso-frontal suture
	Alare (Al)	The most lateral point on each alar contour
	Pronasale (Pn)	The most protruded point of the apex nasi, identified in lateral view of the rest position of the head
	Subnasale (Sn)	The midpoint of the angle at the columella base where the lower border of the nasal septum and the surface of the upper lip meet
Lips	Labiale superius (Ls)	The midpoint of the upper vermilion line
	Stomion (Stm)	The imaginary point at the crossing of the vertical facial midline and the horizontal labial fissure between gently closed lips, with teeth shut in the natural position
	Cheilion (Ch)	The most lateral aspect of the vermilion border of the corner of the subject's mouth

CBCT has become a routine examination for diagnosis and treatment planning in orthodontics.[5] Additionally, CBCT images both soft and hard tissues using the 3D surface volume-rendering technique. However, the soft-tissue images generated using CBCT have low resolution due to light scattering and the presence of imaging artifacts, and cannot capture the actual texture and color of the face. Moreover, the procedure carries the potential risk of radiation exposure, despite the low-level radiation dose.

Three-dimensional photogrammetry involving as the use of facial scanners is available in a variety of imaging systems, and can now be used as an alternative to accurately obtain facial integumentary data.[6,7] Compared with radiation-based systems such as CBCT, facial scanners have the advantages of being less invasive and providing photorealistic images. The primary reason for using facial scanners is that they enable the acquisition of surface data with high-resolution colors relatively quickly. However, they cannot provide information about the presence of impacted teeth, the shape of the root, the relationship between the root and its socket, the occlusal relationship, or skeletal deformities.

In order to overcome the limitations of these 3D imaging devices, numerous studies have attempted to overlay facial scanning images onto CBCT images.[8-10] This image fusion process has been reported not only to facilitate comprehensive diagnosis and treatment planning, but also to improve treatment outcomes. To corroborate the efficacy of this technique, the accuracy of landmark identification in CBCT surface volume-rendered and 3D facial

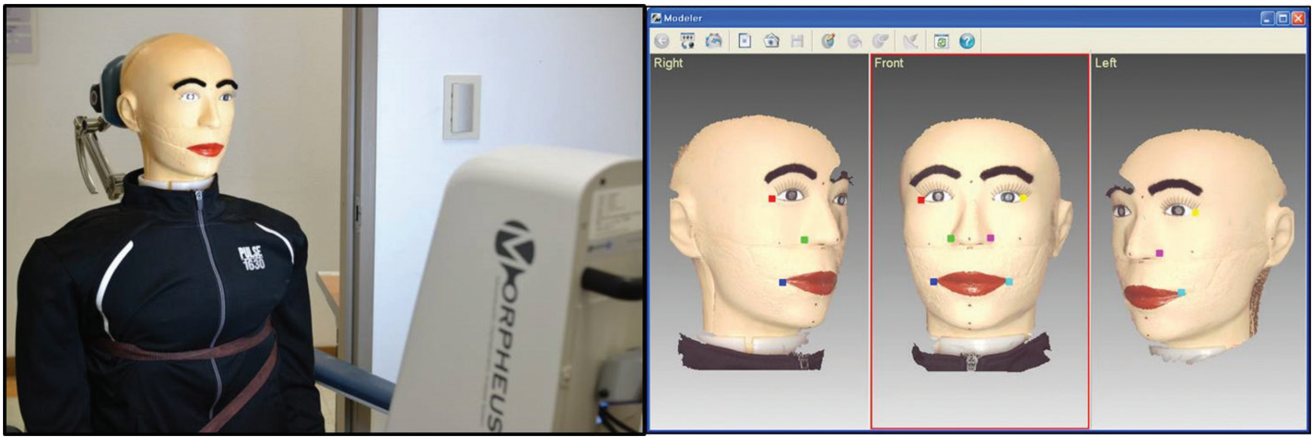

Fig. 2. Three-dimensional facial scan images were obtained using the 3D Neo optical scanning system. Three images were taken at 3 different horizontal angles (frontal, rotated 45° to the left, and rotated 45° to the right), merged, and automatically converted into a single 3-dimensional facial image.

scanning images needs to be confirmed.

In practice, several patient scanning and data reconstruction parameters affect the quality of CBCT images and 3D facial surface model reconstructions.[11,12] It is necessary to assess the impact of these parameters to optimize the quality of these models and protocols for patient scanning, data reconstruction, and 3D surface model generation. This is also important for assessing the accuracy of 3D facial surface models generated by CBCT.

The purpose of this study was to evaluate the accuracy and reproducibility of linear measurements of 3D images generated by CBCT and 3D facial scanning, and to assess the effect of scanning parameters, such as exposure settings, on CBCT images.

Materials and Methods

Phantom

An anthropomorphic phantom (Kyoto Kagaku Co. Ltd., Kyoto, Japan; width × diameter × height: 20 cm × 21 cm × 25 cm) consisting of soft tissues made from a urethane-based resin, a synthetic skull and cervical vertebrae made from an epoxy-based resin, and an acrylic artificial tooth, was used for imaging in this study. The translucent surface of the phantom was coated with paint because the 3D facial scanner could not image translucent objects. Thirteen soft-tissue anatomic landmarks were labeled on the phantom, as defined by Farkas[13] (Fig. 1, Table 1). Radiopaque metallic markers were used as the fiducial points, and these markings reduced random errors, which primarily arose from the placement of the instrument used for measuring anatomic distances.

Image acquisition

Three-dimensional photogrammetry was performed using the 3D Neo optical scanning system (Morpheus Co., Seoul, Korea). This system uses white light from light-emitting diodes as a light source, and is safe for the eyes. The system was easy to use because of its compact size (width × diameter × height: 90 cm × 80 cm × 200 cm), short scanning time (approximately 0.8 seconds), and ease of data transmission over a Wi-Fi network. Additionally, the images acquired using this system are accurate to less than 0.1 mm, according to the manufacturer. The scanning was performed according to the manufacturer's instructions. First, the phantom was positioned, with a natural head position, at a suitable distance of 60-70 cm from the scanner. The Facemaker software provided by the manufacturer (Morpheus Co., Seoul, Korea) was used as stated in the manual to acquire images of the phantom. Three images were acquired at 3 different horizontal angles (frontal, rotated 45° to the left, and rotated 45° to the right), and then merged and automatically converted into a single 3D facial image (Fig. 2).

The CBCT images were acquired using the Alphard-3030 system (Asahi Roentgen Co. Ltd., Kyoto, Japan). The phantom was set up according to the manufacturer's instructions, and the images were obtained after positioning the phantom's head with a head-fixation device. A single 360° rotation, 17-second scan (tube voltage, 80 kVp; current, 8 mA) with a 15.4-cm (diameter) × 15.4-cm (height) field of view was then performed on the phantom, using the Asahi acquisition software (Asahi Roentgen Co. Ltd., Kyoto, Japan). In order to evaluate the influence of various exposure conditions on the CBCT surface volume-rendered images, additional images were acquired under 12 different exposure conditions obtained by combining different tube voltages (70, 75, 80, or 85 kVp) and currents (3, 6, or 9 mA).

Data acquisition and assessment

The direct measurements of the phantom were compared with 15 image-based linear distance measurements using 13 landmarks on the 3D images acquired by CBCT and 3D facial scanning (Table 2).[13] The direct measurements were made using a Cen-Tech 4-inch digital caliper (Harbor Freight Tools, Calabasas, CA, USA) with a precision of 0.01 mm; the exception was the distance between the cheek point and tragus, which was measured with a tapeline. The measurements were repeated 10 times to obtain unbiased values. The mean value of the measurements was designated as the gold standard.

Table 2. Definition of craniofacial surface linear measurements used in this study

Variables	Definition
Ex-Ex	The biocular width
En-En	The intercanthal width
Al-Al	The distance between the most lateral points on the alae
Ch-Ch	The distance between the cheilions of the closed mouth
Tra-Ck (L, R)	The distance between the cheek point and tragus (Left, Right)
N-Pn	The length of the nasal bridge
Sn-Ls	The height of the skin portion of the upper lip
Sn-Stm	The height of the upper lip
Stm-Pog'	The height of the lower lip
Stm-B'	The height of the skin portion of the lower lip
Al-Ch (L, R)	The distance between the alae and cheilion (Left, Right)
Al-Ck (L, R)	The distance between the alae and cheek point (Left, Right)

The image-based measurements were performed using multiple 3D analysis software programs. The CBCT surface volume-rendered images, obtained by manually adjusting the threshold of the image, were reconstructed using OnDemand™ (ver. 1.0, Cybermed Inc., Seoul, Korea), which assisted in the detection of soft-tissue landmarks in the images. The distances between the landmarks were measured using the 3D ruler tool in the OnDemand™ program (Fig. 3A). The same measurements were performed on the 3D facial scanning images using the line length tool in the Morpheus Dental Solution® program (Morpheus Co., Seoul, Korea) provided by the manufacturer (Fig. 3B). The measurements were repeated 10 times to obtain unbiased values. The procedures were repeated 4 weeks later to evaluate the reliability of the measurements. All measurements were performed by the same examiner.

Histograms of the CBCT datasets were prepared and compared to evaluate the effect of various exposure parameters on the 3D images. The datasets were composed of 12-bit depth images with 4096 different gray values, ranging from −1000 to 3095. In order to determine an

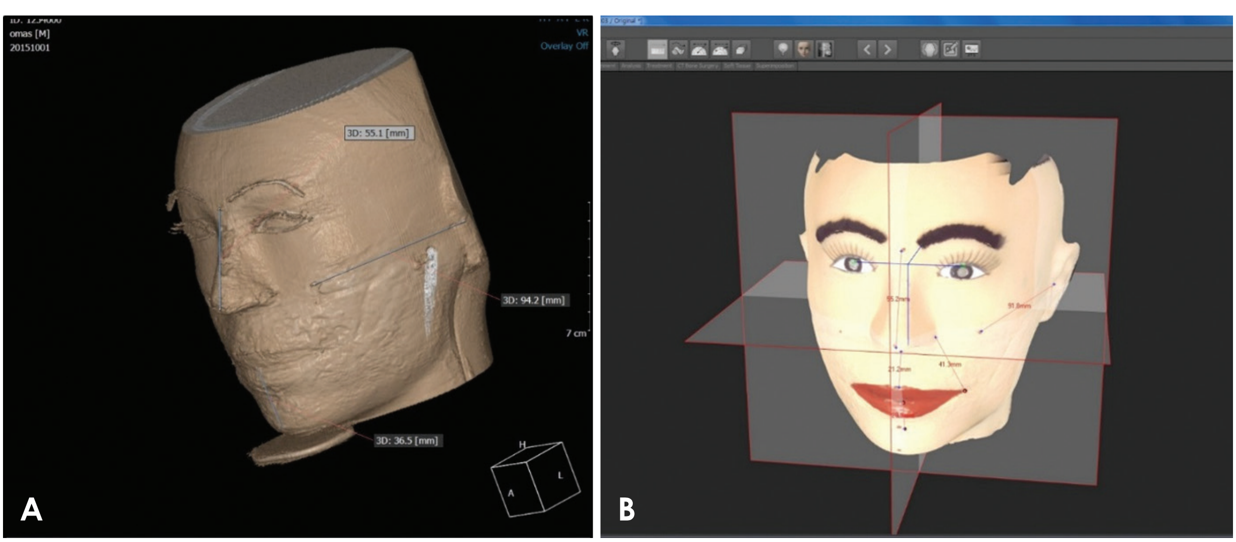

Fig. 3. The image-based measurements were performed using multiple 3-dimensional (3D) analysis software programs. A. The linear measurements of the cone-beam computed tomography surface volume-rendered images were made using the 3D ruler tool in the OnDemand™ software program. B. For 3D facial scan images, the line length tool in the Morpheus Dental Solution® program was used to obtain measurements.

Table 3. Mean differences (mm), discrepancies (%), and *P* values for comparisons of the 2 measurement methods: direct measurements of the phantom versus image-based measurements of cone-beam computed tomography (CBCT) surface volume-rendered images and direct measurements of the phantom versus image-based measurements of 3D facial scans

	Phantom vs. CBCT 3D		Phantom vs. Facial scanner 3D	
	Mean differences	Discrepancy	Mean differences	Discrepancy
Ex-Ex	0.21	0.23	1.04	1.13
En-En	0.13	0.35	0.51	1.36*
Al-Al	0.23	0.61	0.42	1.11
Ch-Ch	0.39	0.57	1.05	1.55*
Tra-Ck (R)	0.60	0.62	1.78	1.85*
Tra-Ck (L)	0.11	0.12	0.01	0.01
N-Pn	0.28	0.51	0.64	1.16
Sn-Ls	0.28	1.24	0.50	2.22*
Sn-Stm	0.16	0.49	0.17	0.52
Stm-Pog’	0.08	0.22	0.30	0.81
Stm-B’	0.45	2.13	0.40	1.89
Al-Ch (R)	0.12	0.28	0.98	2.30
Al-Ch (L)	0.48	1.14	0.00	0.00
Al-Ck (R)	0.10	0.39	0.93	3.60*
Al-Ck (L)	0.40	1.47	0.36	1.33

*$P < .05$

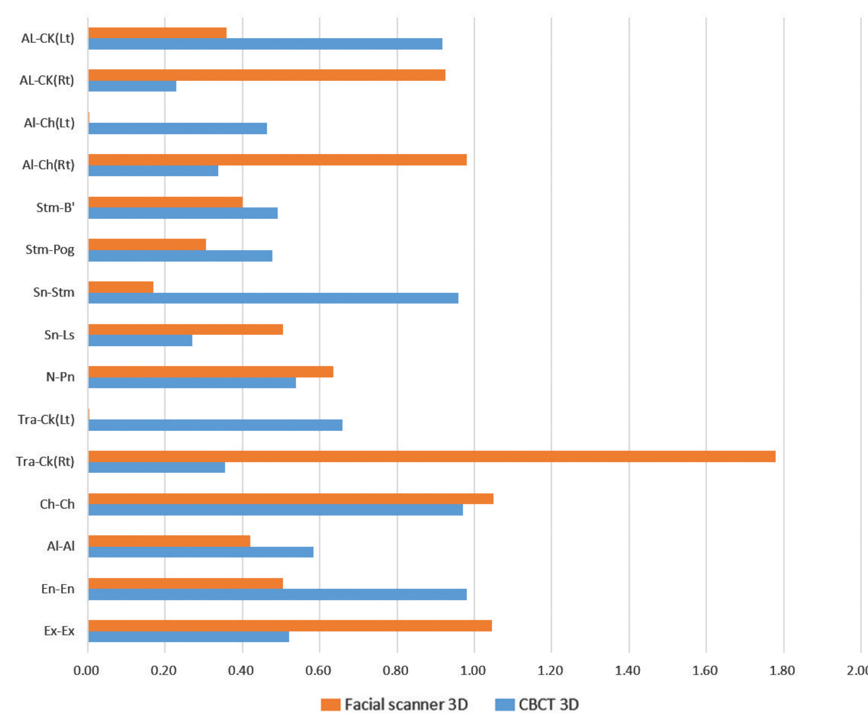

Fig. 4. Comparison of the means of different linear measurements on the phantom and on 3-dimensional images generated by cone-beam computed tomography (CBCT) and facial scanning.

optimal threshold value to distinguish soft-tissue from the background, we compared the CBCT surface volume-rendered images obtained by manually adjusting the threshold of segmentation. The threshold value was set at −600 Hounsfield units to best represent the soft-tissue structures. Next, the images reconstructed using this particular threshold were compared visually.

Statistical analysis

The reproducibility of the measurements was estimated

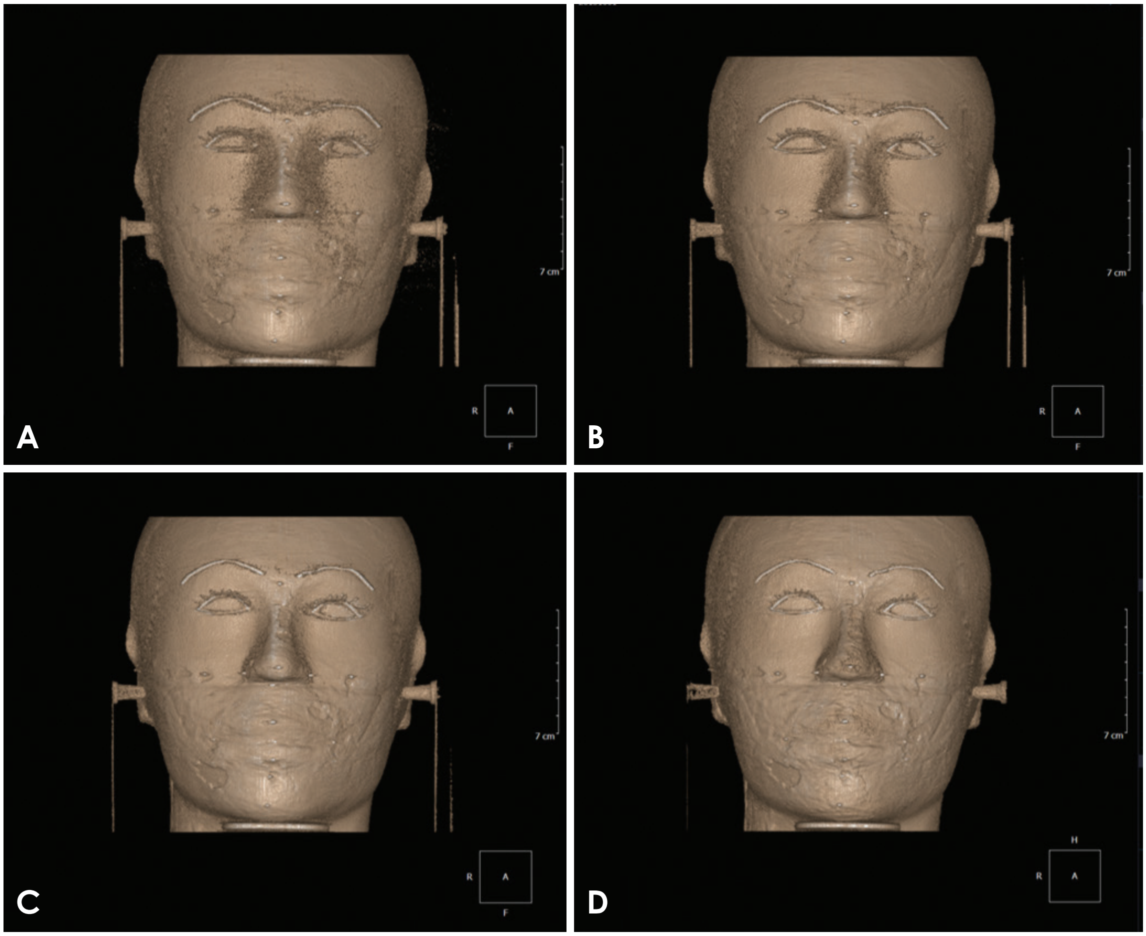

Fig. 5. A visual comparison of cone-beam computed tomography surface volume-rendered images obtained with a constant threshold value of −600 Hounsfield units at different tube voltages. A. 70 kVp. B. 75 kVp. C. 80 kVp. D. 85 kVp. The noise level decreased with increased tube voltage in D, in contrast to A.

using the unpaired 2-sample Student *t*-test for repeated measures. To evaluate the accuracy of the measurements, the differences between the means of the phantom and CBCT measurements and the phantom and 3D scan measurements, the discrepancy (%), and *P* values were assessed using the 1-sample Student *t*-test, following a normal distribution at a 5% significance level. To compare mean values, the paired Student *t*-test was used.

Results

The reproducibility of the measurements was assessed using the unpaired 2-sample Student *t*-test with a significance level of 95%, and no statistically significant differences were found between the first and second sets of measurements.

We evaluated the accuracy of image-based measurements of CBCT surface volume-rendered and 3D facial scan images. None of the measurements of the CBCT surface volume-rendered images were found to be significantly different from their corresponding phantom measurements ($P > .05$); the mean differences of all measurements were less than 1 mm (Table 3, Fig. 4).

In contrast, the 3D facial scan measurements were found to be significantly different from the phantom measurements for 5 of the 15 variables (the intercanthal width, the distance between the cheilions of the closed mouth, the distance between the cheek point and tragus (right), the height of the skin portion of the upper lip, and the distance between the alae and cheek point). Three of the measurements showed mean differences greater than 1 mm: the biocular width (1.04 mm), the distance between the cheilions of the closed mouth (1.05 mm), and the distance between the cheek point and tragus (right) (1.78 mm). The mean differences of the measurements ranged from 0.01 to 1.78 mm (Table 3, Fig. 4).

The quality of the CBCT images at a constant threshold varied with different exposure conditions, thereby affect-

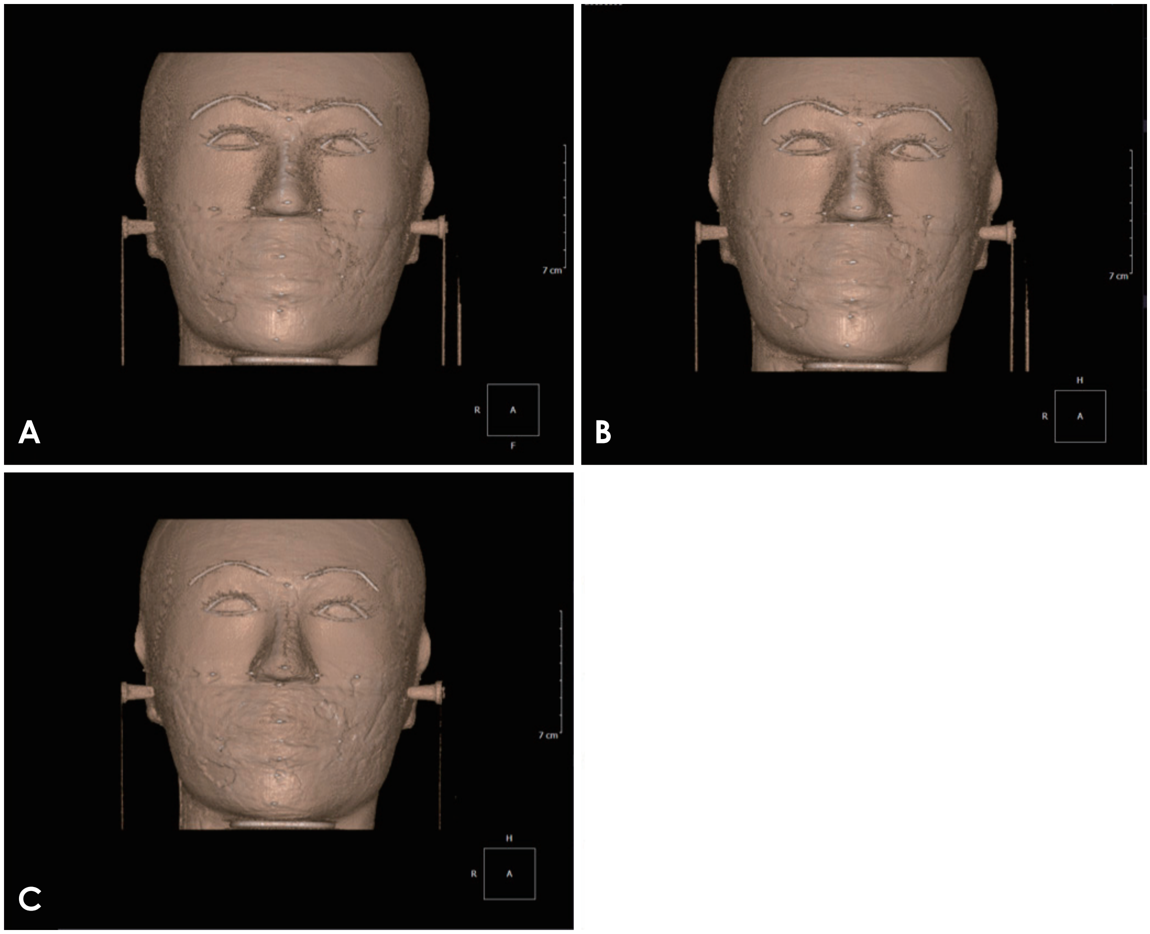

Fig. 6. A visual comparison of cone-beam computed tomography surface volume-rendered images obtained with a constant threshold value of −600 Hounsfield units at different tube currents. A. 3 mA. B. 6 mA. C. 10 mA. The noise level decreased with increased tube current in C, in contrast to A.

ing the reconstruction of the soft-tissue images. Image noise significantly decreased with increased tube voltage and tube current (Figs. 5 and 6).

Discussion

Three-dimensional images provide accurate diagnostic information that enables the formulation of an effective treatment plan and promotes successful treatment outcomes. With advances in the development of 3D imaging equipment, the use and application of 3D imaging technology will undoubtedly expand, particularly in the field of orthodontics. Therefore, it is necessary for 3D imaging to be able to accurately reproduce complicated facial structures in virtual images.

This study evaluated the reproducibility of repeated measurements and compared image-based measurements with direct phantom measurements, which were designated as the gold standard. The iterations of both the direct phantom and image-based measurements showed good congruence.

Additionally, we found that the CBCT image measurements were not significantly different from the direct measurements in this study. This comparison must be made in order to assess the possibility of obtaining accurate 3D facial surface models by CBCT. Previous studies based on dry-skull samples have assessed the accuracy of 3D model reconstructions acquired by CBCT. Those studies have also reported that all CBCT image measurements were found to be satisfactorily accurate compared with the physical measurements.[14-18] Periago et al.[16] reported that many of the linear measurements between cephalometric landmarks on the 3D surface volume-rendered images obtained from CBCT datasets were not significantly different from the anatomical dimensions. Therefore, they could be considered sufficiently accurate for craniofacial analyses. Another study conducted to evaluate the geometric accuracy of CBCT surface volume-rendered images reported high segmentation accuracy.[17]

A facial scanning system was used in a previous study to verify the linear accuracy and precision of virtual imaging techniques, and that system was proven to be a reliable tool for studying facial deformities.[6] Similarly, 3D facial scan images used in another study showed differences of less than 1 mm compared with actual values, and were therefore reported to be sufficiently accurate for clinical practice.[19] The 3D facial scan images evaluated in the present study also demonstrated considerable accuracy, with almost all of the evaluated parameters differing from the actual measurements by less than 1 mm. Our results indicated that the accuracy of linear measurements of 3D facial scans was high enough to ensure a correct diagnosis, as well as for treatment planning and evaluation.

However, some of the measurements of the 3D facial scans showed statistically significant deviations from their corresponding actual values. In particular, the distance between the cheek point and tragus (right) values of the 3D facial scans and those of the phantom showed a mean difference of 1.92 mm. According to Kim et al.,[19] the Morpheus 3D facial scan device generates images by combining data from 3 captures (anterior, right, and left), which could contribute to the distortion in overlapping areas of the images. Unfortunately, there was insufficient information regarding such an error in the image acquisition and processing of the 3D facial scan system. Therefore, further studies are required to clarify the conditions that result in this error and the extent of its effect on the final images. It is also necessary to study the curved distances crossing the integration lines on a phantom or on the actual face of a human subject, which varies in terms of contour, volume, and deformities.

In addition, this study did not perform an evaluation of the soft-tissue anatomy of the throat-chin area because the white-light beam of the Morpheus 3D facial scanner created a ‘dead zone’ and failed to provide accurate data for the submental area. Therefore, advances in the existing scanning equipment are necessary to overcome the limitations identified in this study.

Since our study used an anthropomorphic phantom, it excluded variability caused by changing facial expressions and the contraction of facial muscles during image acquisition and linear measurements. It was also possible to eliminate the influence of changing head positions at the time of image capture and of facial muscle movements during measurements. This improved the accuracy of the measurements and ensured reproducibility.

Previous studies have shown that several scanning and image reconstruction parameters, such as the visibility of anatomical structures, image noise level, and linear accuracy, directly influence the quality of the images acquired with CBCT.[12,20,21] Some variability in image quality is attributable to discrepancies in the CBCT systems, scan protocols, and reconstruction parameters.[20] The quality of images produced by various CBCT parameters, such as the current and voltage settings, the application of a copper filter, and the use of 3 different fields of view, showed significant differences in a previous study.[12] Hassan et al.[22] reported that CBCT surface volume-rendered images were affected by scanning parameters such as the scan field, voxel size, reconstruction parameters, and segmentation threshold selection. Similarly, in this study, the CBCT surface volume-rendered images acquired under different exposure conditions showed visible differences at a constant threshold. This suggests that the optimal threshold value differs according to the exposure conditions. All these factors could jointly affect the quality of the CBCT-reconstructed 3D surface models. Therefore, in order to optimize the scanning, data acquisition, and post-processing protocols, it is necessary to evaluate the parameters that affect image quality.

In conclusion, our results proved that existing 3D imaging techniques were sufficiently accurate for clinical application, diagnosis, and achieving favorable treatment outcomes. Moreover, our results demonstrate that it is critical to optimize parameters that may affect the image acquisition and reconstruction processes of CBCT.

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