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RESEARCH AND EDUCATION

Intraoral digital scans: Part 2—influence of ambient scanning light conditions on the mesh quality of different intraoral scanners

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ABSTRACT

Statement of problem. Digital scans should be able to accurately reproduce the different complex geometries of the patient's mouth. Mesh quality of the digitized mouth is an important factor that influences the capabilities of the geometry reproduction of an intraoral scanner (IOS). However, the mesh quality capabilities of IOSs and the relationship with different ambient light scanning conditions are unclear.

Purpose. The purpose of this in vitro study was to measure the impact of various light conditions on the mesh quality of different IOSs.

Material and methods. Three IOSs were evaluated—iTero Element, CEREC Omnicam, and TRIOS 3—with 4 lighting conditions—chair light, 10 000 lux; room light, 1003 lux; natural light, 500 lux; and no light, 0 lux. Ten digital scans per group were made of a mandibular typodont. The mesh quality of digital scans was analyzed by using the iso2mesh MATLAB package. Two-way ANOVA and Kruskal-Wallis 1-way ANOVA statistical tests were used to analyze the data (á=.05).

Results. Significant differences in mesh quality values were found among the different IOSs under the same lighting conditions and among the different lighting conditions using the same IOS. TRIOS 3 showed the highest consistency and mesh quality mean values across all scanning lighting conditions tested. CEREC Omnicam had the lowest mean mesh quality values across all scanning lighting conditions. iTero Element displayed some consistency in the mesh quality values depending on the scanning lighting conditions: chair light and room light conditions presented good consistency in mesh quality, indicating better mesh quality, and natural light and no light conditions displayed differing consistency in mesh quality values. Nevertheless, no light condition led to the minimal mean mesh quality across all IOS groups.

Conclusions. Differences in the mesh quality between different IOSs should be expected. The photographic scanning techniques evaluated presented higher mesh quality mean values than the video-based scanning technology tested. Moreover, changes in lighting condition significantly affect mesh quality. TRIOS 3 showed the highest consistency in terms of the mean mesh quality, indicating better photographic system in comparison with iTero Element. (J Prosthet Dent 2020;124:575-80)

The integration of intraoral scanners (IOSs) with computer-aided design and computer-aided manufacturing (CAD-CAM) technologies has enabled a fully digital workflow for dental restorative treatment.[1-3] Beyond the operational features of an IOS system, including the speed of use, the need for powder, the size of the intraoral wand and tips, and the cost, important fundamentals such as the technology used, the mesh quality of the obtained data, and the accuracy (trueness and precision) of the system should also be considered.

The relationship between the technology used by an IOS and the accuracy of its acquisition procedure has been studied,[4-16] as well as factors that could impact the accuracy of a digital scan, including handling and the learning curve,[17,18]

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Clinical Implications

Ambient lighting condition is an important factor that affects the mesh quality values or the geometries reproduction capabilities of an intraoral scanner. Depending on the scanner selected and the goal of the digital scan procedure, different lighting conditions are recommended to improve the outcome of the digital scan.

calibration,[19] scanning protocol,[20] ambient light scanning conditions,[21] surface characteristics,[22-27] mobile tissue,[4] reflective restorations, and/or the presence of saliva.[16] However, the authors are unaware of information regarding the mesh quality differences between the different IOS dental systems, which could influence the capabilities of the scanner to accurately reproduce the different complex geometries of the patient's mouth and its relationship with ambient lighting conditions.

IOSs are noncontact optical technologies that can be classified as photographic and videographic systems.[28] Regardless of the type of imaging technology used by an IOS, all cameras require the projection of light that is then recorded as individual images or video and compiled by the software after recognition of the points of interest (POIs). The first 2 coordinates (x and y) of each point are evaluated on the image, and the third coordinate (z) is then calculated by estimating the distance of the specified point from the optical instrument through triangulation.[28]

The multiple sets of points or point clouds generated through the optical sensors are subsequently registered (aligned with respect to each other) and are converted into a surface model represented as a triangle mesh.[29-31] The algorithms used by the IOS software can generate files of varying mesh densities that can be adaptively defined based on the curvature of the region in the mouth; high curvature regions often have highly dense meshing, while relatively flat regions have lower triangle mesh density.[19] The capabilities of the reproduction geometries of an IOS system are determined by its mesh quality.

The purpose of the present study was to measure the impact of various ambient scanning lighting conditions on the mesh quality of 3 different IOS systems. Two independent factors, the lighting condition and the IOS system, were used to compare mesh quality. The null hypotheses were no difference would be found on the mesh quality of the digital scans among the 3 different IOSs under the 4 different ambient scanning lighting conditions evaluated and that no difference would be found on the mesh quality of digital scans under the same light condition among the 3 IOSs analyzed.

MATERIAL AND METHODS

A dental mannequin (Nissim Type 2; Nissim) with a maxillary and mandibular dentate typodont (Hard gingiva jaw model MIS2010-L-HD-M-32; Nissim) was used (Fig. 1). A prosthodontist (M.R.-L.) with 8 years of experience using IOSs recorded different mandibular scans with 3 IOSs following the recommended scanning protocol from each manufacturer. To replicate the clinical environment, the interincisal opening was standardized to 50 mm. In addition, the mannequin was fixed on the head support of a dental chair, and the IOSs were always positioned on the left side of the dental chair. Three IOSs were evaluated (Table 1) at 4 ambient lighting settings (Table 2).

For the CL group, a room with a dental chair (A-dec 500; A-dec) and no windows was selected. The LED light of the chair had an intensity of 15 000 lux and 4100 K oriented 45 degrees at a distance of 58 cm to the mannequin. The room had 6 fluorescent tubes of 54 W, 5000 lumens (GE F54W-T5-841-ECO, Ecolux High Output fluorescent tube; Ecolux Lighting Pvt, Ltd), with a white spectrum color temperature (4100 K) ceiling light. The ambient light condition of 10 000 lux was determined by using a light meter (Digital Light Meter LX1330B; Dr. Meter).

For the RL group, the light of the chair was turned off, and only the ceiling light of the same room was used, with no windows or natural light. The illuminance of the room was 1003 lux, which was measured by using the same light meter. For the ZL group, the same room was used where the light chair and ceiling light were turned off. For the NL group, a room was used with natural light of 500 lux measured by using the same light meter obtained through windows.

Ten digital scans were made for each group in an ambient light scanning setting for a total of 120 digital scans. The mesh quality of the reconstructed model was analyzed by using the iso2mesh MATLAB package.[32]

Element shape metrics were used to measure the quality of the generated mesh. The Joe-Liu quality metric[33,34] was used to measure the quality which was defined as follows:

$$\eta=\frac{2\times\sqrt{2}\times\sqrt{3}S}{\sum_{0\le i\le j<2} l_{ij}^2},$$

where S represented the area of a triangle and l_{ij} denoted the edge length between the i-th and the j-th vertices in the triangle. The range of the Joe-Liu quality was from 0 to 1. A value close to 1 represented higher mesh quality (1 means equilateral triangle), while a value close to 0 means nearly degenerated element.

The statistical aggregates were computed to evaluate the mesh quality and effect of the IOSs and ambient

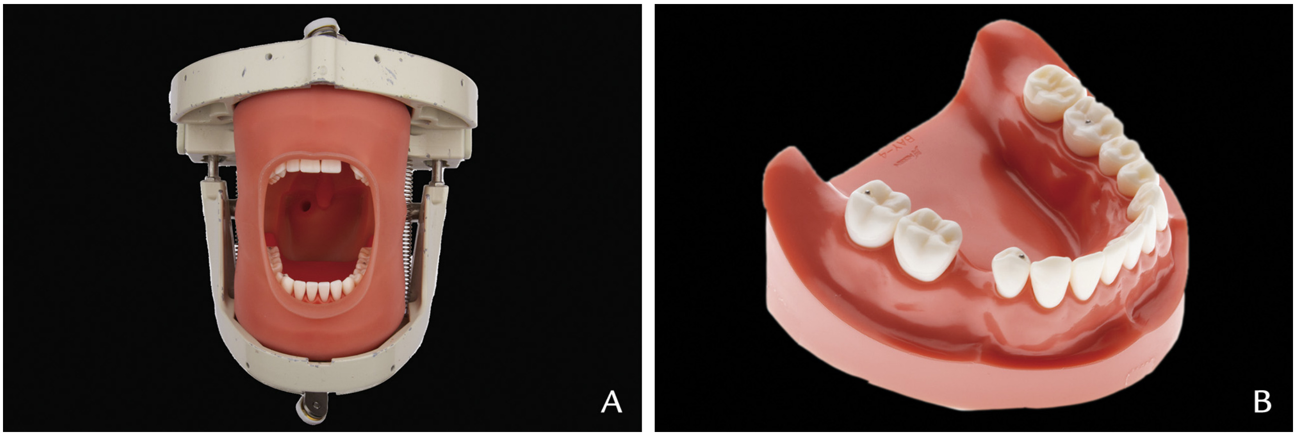

Figure 1. A, Dental simulator model with interincisal opening of 50 mm. B, Mandibular typodont with first right premolar missing.

Table 1. Characteristics of intraoral scanning systems evaluated

Group	Open/Close System	Technology	Powdering	Color Image	Image Type
IOS-1, iTero Element (Cadent LTD)	Open	Parallel confocal microscopy technique Illuminates the surface of the object with three beams of different colored light (red, green, or blue) which combine to provide white light.	No	Yes	Photographic
IOS-2, Omnicam (CEREC-Dentsply Sirona)	Open	Active triangulation (multicolor stripe projection).	No	Yes	Videographic
IOS-3, TRIOS 3 (3Shape A/S)	Open	Confocal microscopy technology. Ultrafast optical sectioning. Light source provides an illumination pattern to cause a light oscillation on the object.	No	Yes	Photographic

scanning light conditions. The mean values of mesh quality of each scan were computed for conducting statistical tests. The normality of the data set was tested by using the Kolmogorov-Smirnov test. Because of the nonnormality of the data, the data were transformed by using the ARTool before a 2-way ANOVA. To investigate further, the Kruskal-Wallis 1-way ANOVA was performed per ambient scanning light condition for each IOS and per IOS for each scanning light condition individually.

RESULTS

Statistical aggregates were computed for each IOS group against each ambient light scanning condition (Table 3). The box plot of the minimum, maximum, interquartile range, medians, and outliers for IOS and ambient scanning light conditions are presented in Figure 2.

The comparison mesh quality of ambient light scanning condition per IOS system showed that the IOS-3 group had the best mesh quality and showed stable quality under 4 different light conditions. Meanwhile, the IOS-1 group showed larger differences under different light conditions than the other IOSs tested. The IOS-2 group performed the worst among the IOSs evaluated. Comparison of mesh quality of each IOS system per lighting condition showed that CL was best among the IOS groups. ZL was worst in IOS-1 and IOS-2 groups.

The Kolmogorov-Smirnov test showed that the data were not normally distributed. Therefore, 2-way ANOVA was not able to directly perform on the original data set. To evaluate the interaction of IOSs and ambient scanning light conditions, the ARTool was selected to perform the aligned rank transformation on the data, and 2-way ANOVA on the transformed data set was conducted. The *P* value of the interaction term of IOS and ambient scanning light conditions was <.05, indicating that there was a significant interaction effect of IOS and ambient scanning light conditions on mesh quality. Furthermore, the *P* value of the main effect terms of IOSs and ambient scanning light conditions was <.05, indicating that both factors had significant main effects on the mesh quality. Multiple comparisons within ambient scanning light conditions (averaged over the levels of ISO) showed that only NL and ZL did not show a significant difference between each other. Multiple comparisons within IOS groups (averaged over the levels of light conditions) showed that all pairs had a significant difference between each other.

To further investigate the effect, the Kruskal-Wallis 1-way ANOVA was conducted per ambient scanning light condition for each IOS individually, and a pair-wise comparison was also performed. In IOS-1 group, 2 pairs

Table 2. Summary of different light conditions settings evaluated

Light Condition	Chair Light 10 000 Lux 4100 K	Room Light 1003 Lux 4100 K	Windows 500 Lux
CL	Yes	Yes	No
RL	No	Yes	No
NL	No	No	Yes
ZL	No	No	No

CL, chair light; NL, natural light; RL, room light; ZL, no light.

(ZL and NL, RL and CL) did not show significant difference because their Bonferroni adjusted P>.05. The P value of the Kruskal-Wallis 1-way ANOVA for the IOS-2 group was >.05. Therefore, there was no significant difference among different light conditions in the IOS-2 group. In the IOS-3 group, a significant difference existed between ZL and CL, NL and CL, and RL and CL.

The Kruskal-Wallis 1-way ANOVA was also conducted per IOS for each scanning light condition individually. The pair-wise comparison was also performed following each test. For the pair IOS-1 and IOS-2, a significant difference was shown under the CL and RL light conditions. Meanwhile, only under RL was there no significant difference between the IOS-1 and IOS-3 groups. Besides, significant differences existed under all 4 light conditions between the IOS-2 and IOS-3 groups.

DISCUSSION

The null hypotheses were rejected, as significant differences in mesh quality values were found between the different IOSs systems tested under the same ambient scanning light conditions and as significant differences were found between the different scanning light conditions by using the same IOS system.

During the acquisition or digitalization of the patient's mouth using an IOS, the point cloud of the geometric samples on the surface of the scanned model are used to extrapolate the shape of the object on the CAD software (Fig. 3). This 3D reconstruction procedure depended on the technology used. Given the differences in the image capture technologies for the IOSs, differences in the mesh quality metrics between the different IOS systems evaluated were expected. In the present study, TRIOS 3 showed the highest consistency and best mesh quality mean values across all scanning lighting conditions tested. Furthermore, CEREC Omnicam presented reasonable consistency in the mesh quality values as the spread obtained was not very high. However, across all scanning lighting conditions, CEREC Omnicam demonstrated the lowest mean mesh quality values. Additionally, iTero Element displayed some consistency in the mesh quality values dependent on the scanning lighting conditions, whereas chair light and room light conditions presented good consistency and better mesh quality than the other ambient light conditions tested; for natural light and no light conditions, the consistency in mesh quality values differed.

Furthermore, in the case of ambient light scanning conditions for a given IOS group, while chair lighting resulted in best mesh quality, TRIOS 3 showed highest consistency in terms of the mean mesh quality, indicating a better photographic system in comparison with iTero Element and higher consistency than the video-based scanning technology used with the CEREC Omnicam system. Zero lighting resulted in the minimal mean mesh quality across all IOS groups.

Recommendations for operating lights and illumination in a dental operatory are limited.[35-37] In 1979,

Table 3. Statistical aggregates of error for all IOS groups (IOS-1 group, iTero Element; IOS-2 group, Omnicam; IOS-3 group, TRIOS 3) against lighting conditions (CL, RL, NT, and ZL)

Lighting	IOS-1 (iTero Element; Cadent LTD) Mean ±standard deviation
CL	0.811 ±0.146
NL	0.803 ±0.161
RL	0.811 ±0.145
ZL	0.797 ±0.167
Lighting	**IOS-2 (Omnicam; CEREC-Dentsply Sirona)**
CL	0.800 ±0.183
NL	0.798 ±0.183
RL	0.798 ±0.182
ZL	0.798 ±0.183
Lighting	**IOS-3 (TRIOS 3; 3Shape A/S)**
CL	0.818 ±0.157
NL	0.815 ±0.158
RL	0.815 ±0.158
ZL	0.814 ±0.158

CL, chair light; NL, natural light; RL, room light; ZL, no light.

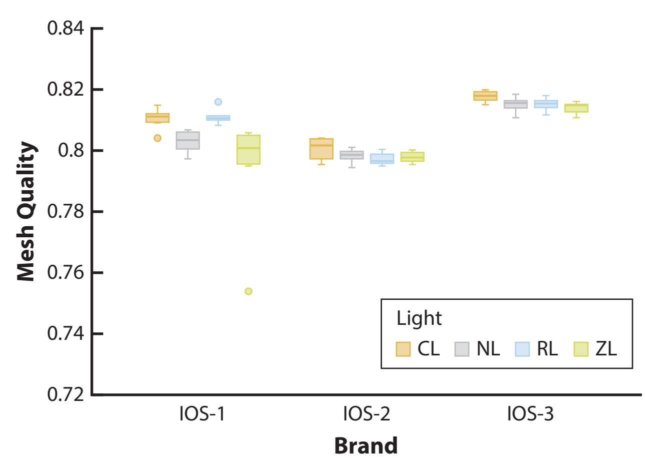

Figure 2. Minimum, maximum, interquartile range, medians, and outliers for trueness and precision of different IOSs (IOS-1 group, iTero Element; IOS-2 group, Omnicam; IOS-3 group, TRIOS 3) and ambient scanning light conditions. CL, chair light; NL, natural light; RL, room light; ZL, no light.

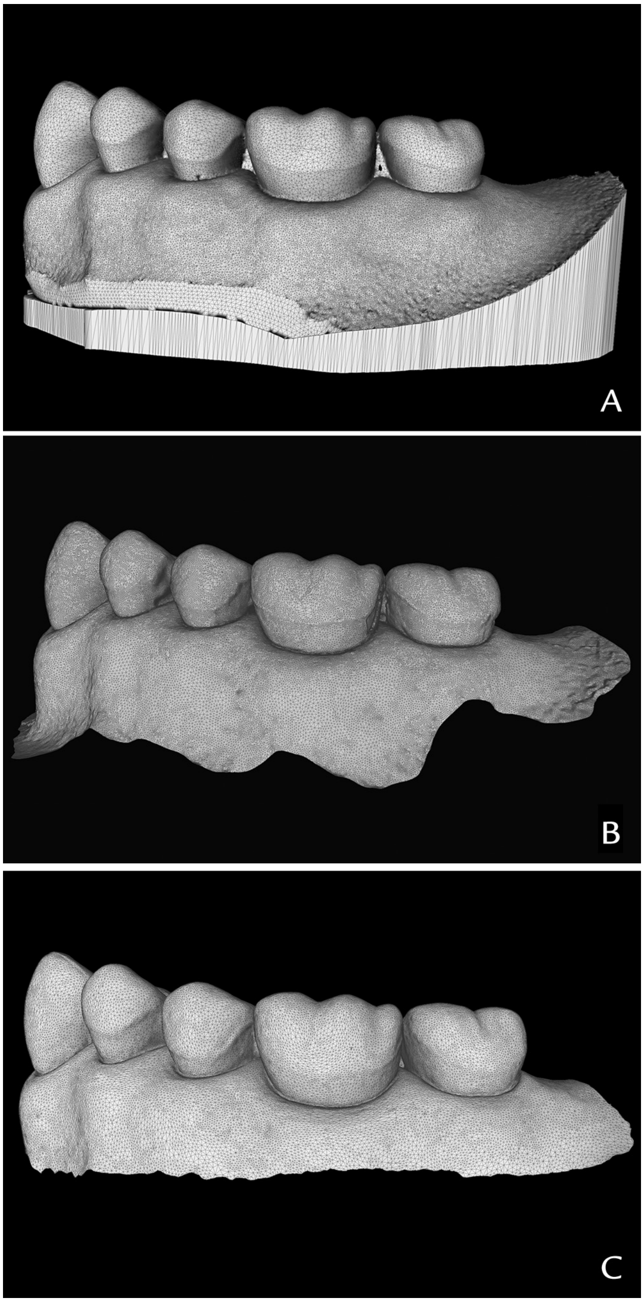

Figure 3. Mesh obtained from different IOS systems evaluated. A, IOS-1 group (iTero Element; Cadent LTD). B, IOS-2 group (Omnicam; CEREC-Dentsply Sirona). C, IOS-3 group (TRIOS 3; 3Shape A/S).

Viohl[35] described 500 lux and 2500 lux as ideal for room light conditions and dental chair illumination, respectively. The European Standard for Illumination (EN 12464) recommended 500 lux for general illumination, 1000 lux for medical or examination rooms, and 10 000 lux for the operating cavity. In the present study, the CL illumination was 10 000 lux, RL 1003 lux, and NL 500 lux, which it is consistent with the recommended European Standards (EN 12464).

Based on the results of the present in vitro study, the standardization of the ambient light scanning conditions in private practice is an important factor for improving the mesh quality of the intraoral digital scan by making well-informed lighting choices based on the make and model of the scanning apparatus. Careful selection can maximize the reproducibility capabilities of the IOS to accurately replicate the different complex geometries of the patient's mouth.

The results of this study were obtained in an in vitro environment with a completely dentate arch. Evaluations of other clinical scenarios using IOSs may change the outcome. Further studies are needed to fully understand the impact of lighting conditions on the mesh quality values of the available IOS systems in a clinical environment. One of the key issues that need further attention is the distinction between the teeth and soft tissue. However, to do this, the current workflow will either require manual segmentation of these 2 regions in the scanned meshes or an automatic computational methodology that performs mesh segmentation. Manual segmentation was avoided in this work because of the size of the data captured and, more importantly, the repeatability of the experiment. As for automatic segmentation, while there are studies[38,39] that have demonstrated such segmentation, it is still an area of research that should be pursued to ensure repeatability of any further analysis. Further investigations are recommended to evaluate individually the mesh quality differences between the teeth and soft tissue.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. Given the differences in the image capture technologies for the 3 IOS evaluated, differences in the mesh quality metrics among the different IOS systems should be expected.
2. The photographic scanning techniques evaluated presented higher mesh quality mean values than those of the video-based scanning technology.
3. TRIOS 3 showed the highest consistency and mesh quality mean values across all scanning lighting conditions tested, indicating a better photographic system than iTero Element. TRIOS 3 under chair lighting conditions obtained the highest consistency in terms of the mean mesh quality value.
4. CEREC Omnicam presented reasonable consistency in the mesh quality values as the spread obtained was not high. However, across all scanning lighting conditions, CEREC Omnicam demonstrated the lowest mean mesh quality values.
5. iTero Element displayed some consistency in the mesh quality values dependent on the scanning

lighting conditions. Chair light and room light conditions presented good consistency in mesh quality, indicating better mesh quality, while for natural light and no light conditions, the consistency in mesh quality values differed.

6. Ambient light scanning conditions influence the mesh quality metrics of the digital scan performed by using any of the 3 intraoral scanners tested. The zero light condition obtained the minimal mean mesh quality across all IOS groups.

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