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Review article

Influence of ambient light conditions on intraoral scanning: A systematic review

Yun Ma [a,b,#], Yong-qing Guo [a,b,#], Mohammed Qasem Saleh [a,b], Hao Yu [a,b,c,*]

[a] Fujian Key Laboratory of Oral Diseases & Fujian Provincial Engineering Research Center of Oral Biomaterial & Stomatological Key Laboratory of Fujian College and University, School and Hospital of Stomatology, Fujian Medical University, Fuzhou, China, [b] Department of Prosthodontics & Research Center of Dental Esthetics and Biomechanics, Fujian Medical University, Fuzhou, China, [c] Department of Applied Prosthodontics Graduate School of Biomedical Sciences, Nagasaki University, Nagasaki, Japan

Abstract

Purpose: To systematically assess the influence of ambient light on the accuracy and scanning time of intraoral scanning.
Study selection: The present systematic review (CRD 42022346672) was registered at the International Prospective Register of Systematic Reviews (PROSPERO) and was performed based on the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020. Electronic searches were conducted using PubMed, Web of Science, and EMBASE, complemented by gray literature, references, and citations of the included studies. The primary outcome was accuracy, and the scanning time was a secondary outcome. Owing to the high heterogeneity, the pooled data were analyzed descriptively.
Results: Six *in vitro* and two *in vivo* experiments were performed. Three *in vitro* studies reported both the accuracy and scanning time of the intraoral scans, whereas the remaining studies exclusively evaluated the accuracy. The studies mainly investigated the influence of illumination levels (0–11000 lux) on intraoral scanning. Intraoral scans revealed optimal accuracy at 1000-lux illumination for complete-arch dentition scans, whereas the influence of illumination levels on 4-unit or shorter scans was not clinically significant. The intraoral scans obtained using confocal microscopy were less affected by the illumination levels than those obtained using the active triangulation technique. Furthermore, the scanning time tended to increase with increasing illumination.
Conclusions: Evidently from the limited number of studies conducted, ambient light illumination had considerable influence on the accuracy and scanning time of intraoral scanning, which appeared to be related to the scanning range and imaging technology.

Keywords: Intraoral scanner, Illumination, Color temperature, Accuracy, Scanning time

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1. Introduction

The introduction and advancements in computer-aided design and computer-aided manufacturing (CAD/CAM) in the dental field have fostered the development of direct digital impression techniques, which can obtain virtual impressions from patients' mouths directly using various intraoral scanners (IOSs)[1,2]. The application of IOSs has improved treatment workflows in prosthodontics, implant dentistry, and orthodontics by simplifying the clinical process, reducing patient discomfort, and increasing cost and time-efficiencies[3–6].

IOSs are composed of a handheld wand (a light projector and camera), computer, and software[7]. By projecting structured light or lasers, cameras in the IOS, such as charge-coupled devices (CCDs), can capture and record the light beams reflected from the illuminated points of the scanned objects[7,8]. The x- and y-coordinates of each point are first recorded, and then the z coordinate is calculated based on various optical imaging technologies (e.g., active confocal microscopy, active triangulation, and active wavefront sampling) [7,9,10]. The performance of IOSs can be influenced by several factors, including the IOS type[11], intraoral conditions[12], scanning protocols[13,14], geometries of the scanned objects[15,16], optical properties of the surface[17,18], processing software algorithms[19,20], and ambient light conditions[21,22]. Thus, ambient light settings have recently attracted considerable research attention because they can be easily controlled during intraoral scanning[23–28].

Ambient light conditions during daily dental practice vary depending on the mixture of light sources used, which are often described by two quantitative parameters: illumination level and color temperature[21]. Illumination level is the total luminous flux incident on a surface per unit area and is measured in lux. Color temperature is a particular temperature measured in kelvin (K), at which the color of light is emitted by an idealized opaque and non-reflective body[23–28]. According to previous studies, the illumination levels

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#Yun Ma and Yong-qing Guo contributed equally to this work.
***Corresponding author:** Hao Yu, Department of Prosthodontics, School and Hospital of Stomatology, Fujian Medical University, Fuzhou, China.
E-mail address: haoyu-cn@hotmail.com

of natural light, ceiling light, and dental chair light combined with a ceiling light were 500, 1000, and 10000 lux, respectively[22,23,27]. The color temperature of a light-emitting diode (LED) light on a chair or a fluorescent tube in a dental office is typically 4100 K[22,23,27]. Numerous studies have evaluated the influence of different ambient light conditions on the accuracy and scanning time of different IOSs; however, their conclusions were inconsistent[21–28]. One study reported that the differences in the accuracy of a Planmeca PlanScan (Planmeca, Finland) in 400–11000 lux illumination range were not clinically relevant (trueness: 39.8–35.2 μm; precision: 16.6–21.6 μm) [25], which was in agreement with another study using five different IOSs[24]. By contrast, one clinical study using Trios 3 (3Shape, Denmark) found that the best trueness of quadrant scans was obtained at 10000 lux and 4100 K, and the largest trueness deviation among all test ambient light conditions was 19.1 μm; furthermore, the best trueness of complete-arch scans was obtained at 1003 lux and 4100 K, and the largest trueness deviation was 48.2 μm[23].

Understanding the influence of ambient light conditions on intraoral scanning can contribute to the efficient use of IOSs. However, such relevant systematic reviews are currently lacking. Therefore, the purpose of this review is to better understand how different illumination levels and color temperatures of ambient light influence intraoral scanning by systematically reviewing the current evidences.

2. Material and Methods

2.1. Protocol and registration

This systematic review (CRD 42022346672) was registered in the International Prospective Register of Systematic Reviews (PROSPERO) and performed according to the guidelines of Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020[29]. The focused question was defined according to the PICO (population, intervention, comparison, and outcome) method[30]: "Are there any differences in the accuracy and scanning time of intraoral scanning between different illumination or color temperatures of the ambient light?"

- Population (P): Data pertaining to teeth or implant scan bodies of models or patients, acquired using IOSs.
- Intervention (I): Ambient light conditions with one illumination or color temperature value.
- Comparison (C): Ambient light conditions with different illuminations or color temperature values.
- Outcome (O): Accuracy, the primary outcome, which includes trueness and precision, and scanning time, the secondary outcome.

2.2. Eligibility criteria

Studies meeting one or more of the following criteria were included. (1) Studies that compared intraoral scans of teeth or implant scan bodies obtained under different ambient light conditions; (2) studies that evaluated at least one of the following outcomes: trueness, precision, and scanning time; and (3) *in vitro* or *in vivo* studies. Conversely, studies meeting one or more of the following criteria were excluded. (1) Case reports, reviews, expert opinions, or clinical guidelines; (2) studies lacking detailed values of both the illuminance and color temperature of ambient light conditions; and (3) studies for which the full text could not be retrieved.

2.3. Information sources and search strategy

An electronic search was conducted initially in PubMed, Web of Science, and Embase on September 19, 2022, with no restrictions on the publication date or language; the search was updated on January 10, 2023. Potential articles were also searched from gray literature using OpenGrey. A manual search was performed in the reference lists and citations of the included studies. The search terms were a combination of MeSH terms and free text terms: ("light" [MeSH Terms] OR "lighting" [MeSH Terms] OR "ambient scanning light" OR "ambient light conditions" OR "illumination" OR "color temperature") AND ("intraoral scans" OR "intraoral scanner") AND ("influence" OR "effect" OR "impact") AND ("accuracy" OR "trueness" OR "precision" OR "time" [MeSH Terms]). The detailed search strategies adapted for each database are presented in Supplementary Information, **Table S1**.

2.4. Study selection

Two independent reviewers (Y.M. and Y.G.) initially screened all the titles and abstracts for potential inclusion. Next, the full texts of the remaining publications that met the eligibility criteria but did not provide sufficient information in the titles and abstracts to allow for a decision were further assessed. Disagreements between the two reviewers were resolved via discussions and consultations with a third reviewer (H.Y.). The level of inter-reviewer agreement was determined using Cohen's kappa statistic (κ-score)[31].

2.5. Data extraction and statistical analysis

Data extraction from the included articles was conducted independently by the same reviewers (Y. M. and Y. G.) using a predetermined table of the study characteristics and results[32–34]. Data on the following characteristics were extracted: author(s), year of publication, study type, sample size, scanned objects, areas of interest, intraoral scanner system(s), ambient light settings, and outcomes evaluated. Owing to the high degree of heterogeneity in the ambient light settings, a meta-analysis was considered inappropriate and only a descriptive analysis was performed[35].

2.6. Risk of bias assessment

The risk of bias in the included *in vivo* studies was assessed using the methodological index for nonrandomized studies (MINORS) scale[36], whereas for the *in vitro* studies, the risk of bias assessment tool was based on a protocol from a previous systematic review[32]. Any disagreements were resolved through discussions.

3. Results

3.1. Study selection

Figure 1 details the entire study selection process, following the PRISMA 2020 flow diagram template. Finally, eight studies were included for qualitative synthesis, and seven studies were excluded. The reasons for the exclusion were: no evaluation of the related outcomes[37–41], no detailed information on the ambient light conditions[42], and no comparisons between different ambient light groups[43]. The κ-score was 0.89 for title/abstract screening and 0.97 for full-text assessment, thus indicating a high level of inter-reviewer agreement[31].

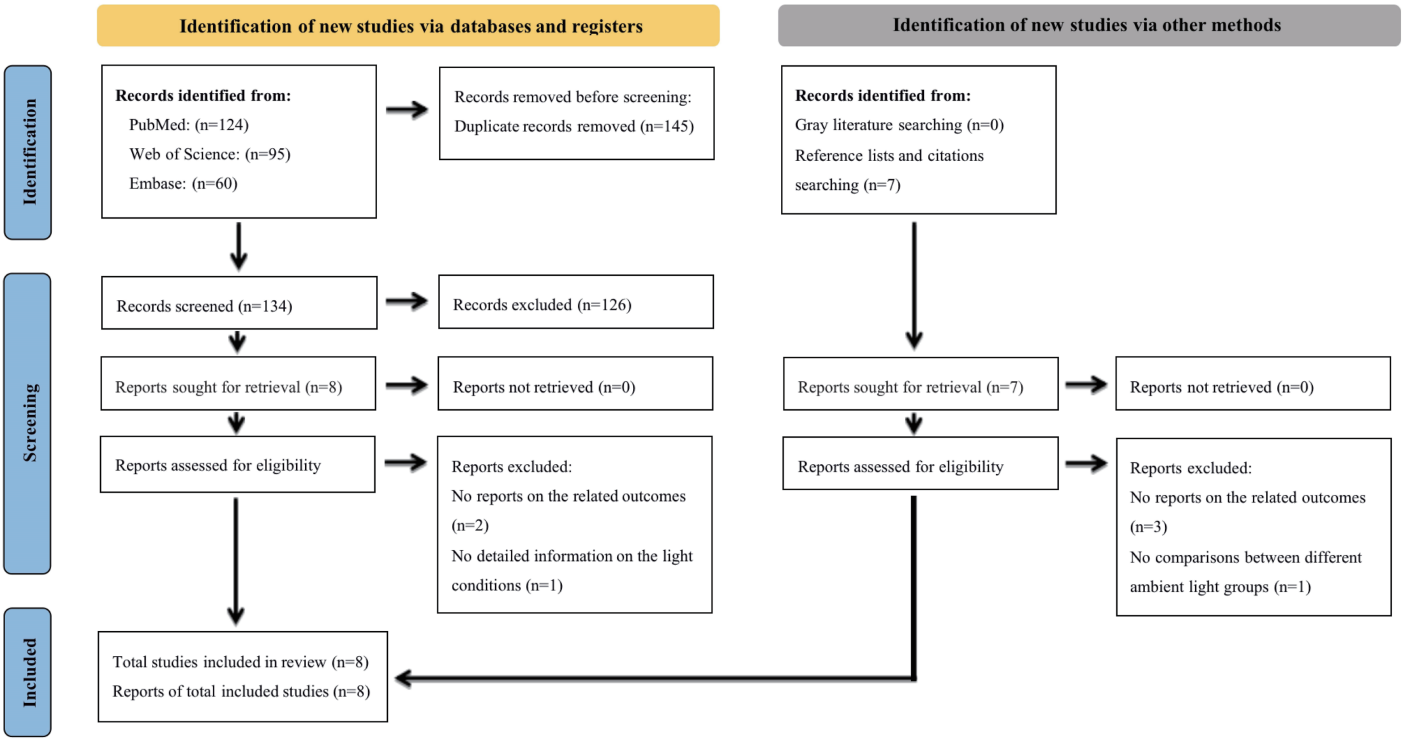

Fig. 1. Flow diagram for study selection

3.2. Characteristics of included studies

The characteristics of the included studies are summarized in **Table 1**. The publication years of the included studies ranged from 2018 to 2022. Two *in vivo* studies were included[23,26], of which one was conducted on one completely dentate volunteer[23], whereas the other was conducted on 20 completely dentate volunteers[26].

In addition, six *in vitro* studies were included[21,22,24,25,27,28], of which five studies employed maxillary or mandibular dentate models the as master models[21,22,24,25,27], whereas one employed an edentulous mandible model containing four implant scan bodies[28].

3.3. Ambient light settings

Details regarding the ambient light settings are presented in Supplementary Information (**Table S2**). The included studies mainly investigated the influence of different illumination levels on intraoral scanning; they were set in the range of 0–11000 lux. Four studies did not set zero-light conditions and were considered as a control group[24,25,27,28]. The commonly evaluated illumination levels were 1000 or 1003 lux (7/8 included studies), 500 lux (5/8 included studies), and 10000 lux (5/8 included studies). The criteria for the test illumination setting in each study are presented in Supplementary Information (**Table S3**).

By contrast, only one study evaluated the influence of different color temperatures (3900, 4100, 7500, and 19000 K) on intraoral scanning[21]. Among the eight included studies, five did not elaborate on the color temperature in detail. The most commonly used color temperature was 4100 K (employed in four included studies).

3.4. Areas of interest

One *in vivo* study evaluated complete-arch dentition scans[26], whereas the other evaluated complete- and quadrant-arch dentition scans[23].

Two *in vitro* studies evaluated complete-arch dentition scans[22,27], two evaluated quadrant-arch dentition scans[21,25], and one focused on both[24]. Furthermore, one *in vitro* study investigated the complete-arch digital implant scans[28].

3.5. Intraoral scanner systems

In this systematic review, 13 different IOSs involving five types of imaging technologies were reported (Supplementary Information, **Table S4**). Of these, five IOSs were evaluated in more than one study; these were: (a) Trios 3 (3Shape, Denmark) (5/8 included studies); (b) iTero Element (Align Technologies, USA), CEREC Omnicam (Dentsply Sirona, USA), CS 3600 (Carestream, USA), and i500 (Medit, South Korea) (2/8 included studies).

3.6. Risk of bias assessment

Overall, the potential bias associated with the absence of a blinded assessment was the most commonly encountered bias in the included studies[21–27]. Other shortcomings included unavailability of calculation of the sample size[21–23,25] and limited number of participants[23] (**Tables 2 and 3**).

3.7. Primary outcome: Accuracy

As defined in ISO 5725-1, accuracy includes trueness and preci-

Table 1. Characteristics of included studies

Author (year)	Study type	Sample size	Scanned objects	Areas of interest	Intraoral scanner systems	Ambient light condition settings	Outcomes evaluated	Main results
Arakida *et al.* (2018) [21]	*in vitro*	5 scans per group	A mandibular dentate typodont	First premolar to second molar	True Definition (3M, USA)	12 ambient light conditions: combinations of 3 illumination (0, 500, and 2500 lux) and 4 color temperature (3900, 4100, 7500, and 19000 K)	Trueness, precision (3D surface deviation)/ scanning time	Trueness: the best was obtained at 500 lux with 3900 K (59.8 μm) and the worst was obtained at 2500 lux with 3900 K (63.8 μm). Precision: n.s. Scanning time: regardless of the color temperature, groups of 2500 lux (62.0~82.2 s) were longer than groups of 0 lux and 500 lux (51.8~58.8 s).
Revilla-León *et al.* (2020a) [22]	*in vitro*	10 scans per group	A mandibular dentate typodont in a dental simulator mannequin	Complete arch	iTero Element (Align Technologies, USA)/ CEREC Omnicam (Dentsply Sirona, USA)/ Trios 3 (3Shape, Denmark)	4 ambient light conditions (illumination and color temperature): 0 lux, 0 K/500 lux, NR/1003 lux, 4100 K/10000 lux, and 4100 K	Trueness, precision (3D surface deviation)	The ambient light conditions at which the best accuracy was obtained: iTero Element (1003 and 10000 lux, 4100 K)/ CEREC Omnicam (0 lux, 0 K)/ Trios 3 (1003 lux, 4100 K)
Revilla-León *et al.* (2020b) [23]	*in vivo*	10 scans per volunteer per group (1 volunteer)	Complete maxillary dentition of the volunteer	Complete arch/ right quadrant-arch	Trios 3 (3Shape, Denmark)	4 ambient light conditions (illumination and color temperature): 0 lux, 0 K/500 lux, NR/1003 lux, 4100 K/10000 lux, and 4100 K	Trueness, precision (3D surface deviation)	Right quadrant-arch scans: the best trueness was obtained at 10000 lux with 4100 K (28.7 μm) and the worst was obtained at 1003 lux with 4100 K (47.8 μm). Complete-arch scans: the best trueness was obtained at 1003 lux with 4100 K (43.9 μm) and the worst was obtained at 0 lux (92.1 μm).
Wesemann *et al.* (2021) [24]	*in vitro*	17 scans per group	A maxillary dentate resin model fixed with a lightly dusted alloy structure	Left first premolar to second molar/ right first premolar to second molar/ left first premolar to right first premolar/ complete-arch	Trios 3 (3Shape, Denmark)/ CEREC Omnicam (Dentsply Sirona, USA)/ iTero Element (Align Technologies, USA)/ CS 3600 (Carestream, USA)/ Planmeca Emerald (Planmeca, Finland)/ Aadva (GC, Japan)	4 ambient light conditions (illumination and color temperature): 100 lux, 5600 K/500 lux, 5600 K/1000 lux, 5600 K/5000 lux, and 5600 K	Trueness, precision (distance deviation)/ scanning time	The difference in the accuracy of 4-unit scans among groups had no clinical relevance. The ambient light conditions at which the best accuracy of complete-arch scans were obtained: Trios 3 (trueness: n.s.; precision: n.s.)/ Cerec Omnicam (trueness: 100, 500, and 5000 lux; precision: n.s.)/ iTero Element (trueness: 100, 1000, and 5000 lux; precision: n.s.)/ CS 3600 (trueness: 5000 lux; precision: n.s.)/ Planmeca Emerald (trueness: 100, 1000, and 5000 lux; precision: n.s.)/ Aadva (trueness: n.s.; precision: 100 and 1000 lux) The ambient light conditions at which the shortest scanning times were obtained: Trios 3 (500 lux)/ Cerec Omnicam (100 lux)/ iTero Element (100 and 5000 lux)/ CS 3600 (500 lux)/ Planmeca Emerald (100 lux)/ Aadva (500 lux)
Jivanescu *et al.* (2021) [25]	*in vitro*	5 scans per group	A mandibular dentate typodont in a dental simulator mannequin	Full-crown prepared right mandibular first molar	Planmeca Emerald (Planmeca, Finland)	6 ambient light conditions (illumination and color temperature): 400 lux, NR/1000 lux, NR/3300 lux, NR/3800 lux, NR/10000 lux, NR/11000 lux, NR	Trueness, precision (3D surface deviation)	Trueness: n.s. Precision: the difference between groups had no clinical relevance.
Koseoglu *et al.* (2021) [26]	*in vivo*	1 scan per volunteer at each group (20 volunteers)	Complete maxillary dentition of the volunteer	Complete arch	i500 (Medit, South Korea)	2 ambient light conditions (illumination and color temperature): 0 lux, 0 K/1003 lux, NR	Trueness (3D surface deviation)	The best trueness (72.3 μm) was obtained at 1003 lux with blue mode and the worst was obtained at 0 lux with white mode (88.4 μm).

Table 1. Coninued

Author (year)	Study type	Sample size	Scanned objects	Areas of interest	Intraoral scanner systems	Ambient light condition settings	Outcomes evaluated	Main results
Revilla-León *et al.* (2021) [27]	*in vitro*	10 scans per group	A mandibular dentate typodont in a dental simulator mannequin	Complete arch	Trios 3 (3Shape, Denmark)	10 ambient light conditions (illumination, color temperature): 1000 lux, 4100 K/2000 lux, 4100 K/3000 lux,4100 K/ 4000 lux, 4100 K/5000 lux, 4100 K/6000 lux, 4100 K/ 7000 lux, 4100 K/8000 lux, 4100 K/9000 lux, 4100 K/ 10000 lux, and 4100 K	Trueness, precision (3D surface deviation)	The best trueness (26.3 μm) and precision (40.0 μm) were obtained at 1000 lux and the worst at 5000 lux (trueness: 46.3 μm, precision: 99.9 μm).
Ochoa-López *et al.* (2022) [28]	*in vitro*	10 scans per group	Four nearly parallel titanium scan bodies in an edentulous mandibular resin model	Complete arch	Trios 3 (3Shape, Denmark)/ CEREC Primescan (Dentsply Sirona, USA)/ iTero Element 5D (Align Technologies, USA)/ i500 (Medit, South Korea)/ i700 (Medit, South Korea)/ CS3600 (Carestream, USA)/ CS3700 (Carestream, USA)	5 ambient light conditions (illumination and color temperature): 100 lux, NR/500 lux, NR/1000 lux, NR/5000 lux, NR/10000 lux, NR	Trueness, precision (3D surface deviation)/ scanning time	The ambient light conditions at which the best accuracy values obtained: Trios 3, iTero Element 5D, and CS3700 (100 lux)/ CS3600 (500 lux)/ i500 (1000 lux)/ i700 (5000 lux)/ Primescan (10000 lux) The ambient light conditions at which the shortest scanning times were obtained: Trios 3 (500, 1000, and 5000 lux)/ iTero Element 5D (100 and 5000 lux)/ Primescan (100, 500, 1000, and 5000 lux)/ CS 3600 (100 lux)/ CS 3700 (100 and 500 lux)/ i500 (10000 lux)/ i700 (100, 500, and 1000 lux)

n.s.: not significant, NR: not reported

Table 2. Risk of bias assessment in *in vivo* studies according to MINORS scale

Authors (year of publication)	A clearly stated aim	Inclusion of Consecutive Patients	Prospective Data Collection	Endpoints appropriate to the aim of the study	Unbiased assessment of the study endpoint	Follow-up period appropriate to the aim of the study	Loss to follow up less than 5%	Prospective calculation of the study size	An adequate control group	Contemporary groups	Baseline equivalence of groups	Adequate statistical analysis	Total MINORS score
Revilla-León *et al.* (2020b) [23]	2	0	2	2	0	2	2	1	1	2	2	2	18/24
Koseoglu *et al.* (2021) [26]	2	1	2	2	0	2	2	2	1	2	2	2	20/24

0=not reported, 1=reported inadequately, 2=reported adequately; ideal global score was 24 points for comparative studies

sion. Trueness describes the discrepancy between the intraoral scans and reference objects, whereas precision indicates the differences among repeated intraoral scans under identical conditions[44]. Eight studies compared the accuracy of each IOS under different ambient light conditions[21–28]. Regarding the measured parameters, seven studies measured the 3D surface deviation[21–23,25–28] by superimposition, and one measured the distance deviation[24]. All the studies used the same method to calculate the trueness, which entailed comparing the test scans with the reference data. However, for precision, the methods varied among the studies; some calculated the deviation between sets of paired scan data within the same test group[21,25,28], whereas others calculated the standard deviation[22–24] or interquartile range[27] of the discrepancies among all the test scans and the reference data.

3.8. *Accuracy by scanning range*

Among the complete-arch dentition scans, ambient light conditions exhibited a general influence. In an *in vivo* study evaluating the Trios 3, an illumination of 1003 lux (trueness: 43.9 μm) was recommended, and the worst trueness was observed under zero light conditions (92.1 μm)[23]. Furthermore, the other *in vivo* study[26] using the i500 in white- and blue-light modes revealed that the best trueness was at 1003 lux illumination with blue mode (72.3 μm), and the worst trueness was at zero light condition with white mode (88.4 μm).

In an *in vitro* study by Revilla-León *et al.*[22], significantly better accuracy was observed under 1003- and 10000-lux illumination for

Table 3. Risk of bias in the *in vitro* studies

Authors (year of publication)	Sample size calculation	Single operator	Stable ambient light condition setting protocol	Scanning protocol	Accurate method for accuracy measurement	Statistical analysis	Blinded examiner
Arakida *et al.* (2018)[21]	N	N	Y	Y	Y	Y	N
Revilla-León *et al.* (2020a)[22]	N	Y	Y	N	Y	Y	N
Wesemann *et al.* (2021) [24]	Y	N	Y	Y	Y	Y	N
Jivanescu *et al.* (2022)[25]	N	Y	Y	Y	Y	Y	N
Revilla-León *et al.* (2021) [27]	Y	Y	Y	Y	Y	Y	N
Ochoa-López *et al.* (2022)[28]	Y	Y	Y	Y	Y	Y	Y

Specific parameters reported or not were recorded with "Y" or "N"

iTero Element, under 0-lux illumination for CEREC Omnicam, and under 1003-lux illumination for Trios 3, compared with other test ambient light conditions. The largest differences in trueness and precision were 146.0 μm and 195.8 μm, respectively. In another *in vitro* study by the same research group, the best and worst accuracies of Trios 3 were found at 1000 and 5000 lux, respectively (trueness: 26.3–46.3 μm, precision: 40.0–99.9 μm)[27]. In the *in vitro* study by Wesemann *et al.*[24], compared with other illumination groups, better trueness of the iTero Element and Planmeca Emerald (Planmeca, Finland) were both achieved under illuminations of 100, 1000 and 5000 lux, whereas Cerec Omnicam and CS 3600 had better trueness under 5000 lux. By contrast, the precision of these four IOSs was not influenced by the illumination levels. Aadva (GC, Japan) achieved better precision under 100- and 1000-lux illuminations; however, the trueness among the test illumination levels showed no significant differences.

Regarding the quadrant-arch dentition scans, the effects of ambient light conditions in most studies appeared to be clinically insignificant. One *in vivo* study reported obtaining the best trueness of the right quadrant scans using Trios 3 at an illumination of 10000 lux (28.7 μm) and the worst was at 1003 lux (47.8 μm)[23]. Conversely, Arakida *et al.* evaluated the scans from the first to second molar in a dentate typodont using True Definition (3M, USA)[21]. In that study, although the condition of 500 lux at 3900 K was recommended, the largest difference in trueness was merely 4 μm compared with the other conditions[21]. One *in vitro* study by Jivanescu *et al.*[24,25], which focused on the scans of one full-crown prepared molar, reported that the precision ranged from 16.6 to 21.6 μm under an illumination of 400–11000 lux. Moreover, no significant difference was noted in the trueness between the ambient light groups. Some other studies on scans of 4-unit teeth revealed similar results[24,25].

3.9. Accuracy by imaging technology

IOSs with confocal microscopy (Trios 3, iTero Element, iTero Element 5D (Align Technologies, USA), Primescan (Dentsply Sirona, USA)) and active triangulation techniques (CEREC Omnicam, Planmeca PlanScan, Planmeca Emerald, CS3600, and CS3700 (Carestream, USA)) were the most commonly used in the included studies. In confocal microscopy, the probe light is projected through an aperture and focused by confocal optics into a small focal volume. Only the reflected light from the in-focus scanned surface, which contains the position information, is collected into the detector aperture. By contrast, in the active triangulation technique, the light source, camera, and illuminated point form a triangle, and the position information of the scanned surface is directly determined by trigonometric calculation[9].

The results of the included studies indicate that the optimal ambient light conditions for IOSs using identical imaging technology were not identical. However, relatively fewer accuracy changes among different ambient light conditions were observed in the IOSs with the principle of confocal microscopy compared with those with the active triangulation technique. In one study using four different conditions with 0–10000 lux illumination, the trueness of Trios 3 ranged from 92.2 to 139.2 μm, and that of iTero Element ranged from 71.9 to 88.6 μm, whereas that of CEREC Omnicam ranged from 247.0 to 393.1 μm[22]. In another study with four illumination conditions (100–5000 lux), the trueness of Trios 3 was not affected by the illumination, and the trueness of iTero Element ranged from 122 to 180 μm. Moreover, the trueness of Planmeca Emerald ranged from 22 to 342 μm, and that of CS 3600 ranged from 54 to 211 μm[24].

3.10. Secondary outcomes: scanning time

Three studies additionally recorded and analyzed the associated scanning times. In one study with 100–5000 lux illumination setting, CEREC Omnicam and Planmeca Emerald required the shortest scanning time in the 100-lux group, whereas Aadva and CS 3600 required the shortest scanning time in the 500-lux group[24]. In another study, regardless of the color temperature adopted, True Definition required the shortest scanning time (51.8–58.8 s) under 0 and 500 lux illuminations, and the longest scanning time (62.0–82.6 s) under 2500-lux illumination. A positive relationship was observed between the scanning time and increasing illumination[21]. Similarly, in the study by Ochoa-López *et al.*[28], the scanning times of i700 (Medit, South Korea) (96.5–170.5 s), CS3600 (134.5–235.0 s), and CS3700 (127.5–200.0 s) increased with increasing illumination.

Additionally, as confirmed by the consistent results in two studies[24,28], Trios 3 was faster under 500, 1000, and 5000 lux illuminations. The scanning times of the iTero Element and iTero Element 5D exhibited similar changes, in which one peak at 1000 lux exhibited the longest scanning time among all the tested illumination levels.

4. Discussion

To the best of our knowledge, this is the first systematic review comparing the outcomes of intraoral scanning under different ambient light conditions. Previous studies on this subject have primarily evaluated the influence of ambient light illumination level on intraoral scanning. This review established the general influence of illumination on intraoral scanning in terms of accuracy and scanning time. However, their influences on different IOSs were not the same. Moreover, these influences were related to the scanning range and imaging technology.

As part of the digital treatment workflow, the scanning deviation should be as small as possible to leave greater tolerance for errors in the subsequent steps[45]. Based on these results, the influence of ambient light conditions was associated with the scanning range. Regarding the complete-arch dentition scans, the largest trueness difference was up to 320 μm[24]. Except for CEREC Omnicam and CS 3600, the IOSs consistently demonstrated optimal accuracy at an illumination of 1000 lux. Moreover, the accuracies of the aforementioned IOSs obtained at 1000 lux were not the least among the tested illumination levels. Conversely, when focusing on 4-unit or shorter scans, the differences in the accuracies among different illumination levels showed limited clinical relevance.

Currently, in addition to the common major imaging technology, different IOSs integrate their own unique designs, techniques, and algorithms, on which little information is disclosed by the manufacturers[42,46–48]. This might explain why even IOSs using the same imaging technology showed contrasting results. Nonetheless, a relatively smaller effect of ambient light was observed on the IOSs using the confocal microscopy technique compared with those with the active triangulation technique. In confocal microscopy, the detector aperture in the IOSs can obstruct light from the out-of-focus planes; thus, only in-focus images are acquired, which may reduce the impact of ambient light and result in a sharper image[9,47,49].

The scanning time is related to the patient's experience[3]. For the majority of IOSs, especially those using the active triangulation technique (e.g., CEREC Omnicam, Planmeca Emerald, CS 3600, and CS 3700), the scanning time demonstrated an increasing trend with increasing illumination level. A longer scanning time is generally considered likely to increase the image number, which may generate more inherent errors from stitching, and thus compromise the scanning accuracy[50]. However, in the included studies, time changes with the illumination levels did not coincide with those of the accuracy. When the scanners were in operation, the high intensity of the light caused saturation in the CCD and consequently delayed the capture of the positions of the points[41]. During this process, the scanning time increased; however, as no images were captured, the accuracy was not affected.

Theoretically, the CCD not only captures the light projected from the scanners but also collects ambient light at the same wavelength, which may disturb the accurate calculation of the coordinates of each point. However, only a few studies have recommended zero-light conditions[22]. Surprisingly, the worst results were obtained when no light was used in previous studies[22,23,26]. This finding also indicates that providing proper ambient light during scanning might be beneficial to the performance of the IOSs. Based on the present findings, when scanning complete-arch dentition, an illumination of 1000 lux is recommended to achieve preferable accuracy. Although the scanning time taken at this illumination level may not be the shortest, priority should be given to accuracy owing to its influence on the long-term success of treatment.

Note that four out of the eight articles included in this review were predominantly derived from the same research group[22,23,27,28], and only a small number (n = 2) of clinical studies with small sample sizes were available[23,26]. The typodont was set inside a dental mannequin in three *in vitro* studies to simulate some of the clinical circumstances[22,25,27]. However, the resin materials have optical properties that differ from those of natural teeth and mucosa[17,51]. Saliva and differing humidity in the mouth can also change the light reflection behavior[42,52,53]. Moreover, three of the six *in vitro* studies did not use a simulator mannequin, although the method for ensuring the stability of the test light source was described in some of the articles[21,24,28]. Hence, caution should be exercised regarding the generalizability of the results, particularly in clinical applications. In the present review, the influence of illumination level on intraoral scanning was evaluated. Few studies have focused on color temperature. Notably, for the test illumination setting, the European Standard for Illumination was commonly adopted in previous studies, including those involving real clinical light situations[22,23,25–27]. However, this standard may differ from the standards used in other regions of the world and from the intraoral light conditions. Thus, further systematic analysis of the influence of illumination and color temperature is required to confirm the current conclusions.

5. Conclusions

Based on the currently limited evidence, the following conclusions can be drawn.

1. The illumination level of the ambient light is the primary source of influence on intraoral scanning; the illumination level appears to be associated with the scanning range and imaging technology. However, few studies have focused on the color temperature.
2. For complete-arch dentition scans, the IOSs revealed optimal accuracy under 1000-lux illumination. However, for the 4-unit or shorter scans, the influences were not clinically relevant. The influence of ambient light on the IOSs, as measured with confocal microscopy was less than that measured with the active triangulation technique.
3. The scanning time exhibited an increasing trend with increasing illumination level for most IOSs, particularly with regard to the values obtained with the active triangulation technique.

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Conflict of interests

The authors declare no conflict of interests.

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