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In vitro assessment of an intraoral scanner accuracy on abutments with horizontal preparation geometries and subgingival margins

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ABSTRACT

Objectives: This study evaluated the accuracy of the Medit i700 intraoral scanner (IOS) in capturing horizontal tooth preparations at different depths below the gingival margin and assessed its ability to detect surfaces beyond the finish line.
Methods: Using CAD software, two abutments of a standard maxillary first molar were designed with horizontal preparation and 0.8 mm chamfer at 1 mm and 2 mm depths below the gingival margin. The abutment designs, created in DentalCAD 3.0 Galway (Exocad), were 3D printed and mounted on a typodont with simulated pink gum. An experienced operator conducted 20 scans, with each scan taking between 1 and 2 min. The scanning process began at the occlusal surface of the right third molar and proceeded longitudinally to the contralateral molar, then extended buccally and palatally, resulting in two experimental groups: H-1 (1 mm depth) and H-2 (2 mm depth). Accuracy was assessed using Geomagic Control X software, with descriptive statistics and independent sample tests ($\alpha = 0.05$) employed for group comparisons.
Results: No statistically significant difference was found in trueness between H-1 and H-2 (p=.053). However, precision differed significantly (p<.001). The IOS could not capture surfaces beyond the finish line in horizontal preparations.
Conclusions: Within study limitations, the horizontal preparation design hindered the IOS's ability to capture tooth anatomy beyond the finish line. Nonetheless, accuracy values at both 1 mm and 2 mm depths were clinically acceptable.
Clinical Significance,: The present study shows that the tested intraoral scanner is accurate enough to scan abutments with horizontal margins placed 1 and 2 mm below the gingiva.

1. Introduction

Over the past few decades, the widespread integration of digital technologies in dentistry, coupled with the introduction of increasingly advanced restorative materials, has brought about significant shifts in prosthetic approaches. Notably, intraoral scanners (IOSs) are gaining prominence in daily practice [1] due to a host of undeniable advantages: patients overwhelmingly prefer scans over conventional impressions, resulting in reduced stress and discomfort [2,3]; they streamline and expedite clinical procedures [4]; they remain unaffected by dimensional changes of impression materials and gypsum [2]; they facilitate the transition to fully digital workflows in restorative planning [5]; they enhance communication within the dental team, laboratory, and patient [4]; and, importantly, they eliminate the need for storing and disposing of casts [6].

In prosthodontics, the latest IOSs demonstrate clinically acceptable accuracy in producing both implant- and tooth-supported restorations for horizontal and vertical tooth preparation designs [7–10], irrespective of abutment geometry [11]. However, a critical issue arises in detecting anatomical information when the finish line is deeply positioned in the gingival sulcus [12]. As defined in the Glossary of Prosthodontics Terms, the "finish line" or "margin" of an abutment refers to

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"the junction of prepared and unprepared tooth structure with the margin of a restorative material" [13]. It is crucial to adequately record marginal anatomy and over-preparation areas in both conventional impression and digital scanning procedures to achieve an acceptable marginal fit of the restoration [14] and provide the dental laboratory with valuable information about tooth contour [15].

With the use of IOSs, an in vitro study demonstrated that the supragingival finish design is better detected than when it is equigingivally located [16]. Additionally, clinical factors such as the proximity of teeth or the marginal gingiva noticeably affect the final result [17]. Conversely, conventional elastomeric impression materials can penetrate more deeply into the gingival sulcus, reproducing apical details due to their rheological properties [18]. The conventional impression, especially when employing the 2 materials/2 times impression technique, can be a viable solution to record both the subgingival finish line and an apical portion of tooth anatomy beyond it [19,20]. In order to expose the finish line of the subgingival preparation, different gingival retraction approaches have been described, such as the use of retraction cords, electrosurgery, expanding foams, or laser systems [21].

Numerous in vitro and in vivo studies compare digital scans with conventional impression-making procedures, consistently reporting better results in terms of trueness and precision for IOSs [8,22–23]. Studies also compare different IOS devices available on the market [24–25], and various scanning strategies for implant abutments, natural tooth abutments, and fully edentulous ridges have been explored [26–28].

A key study by Nedelcu et al. examined the ability of seven different intraoral scanners to capture finish lines and overall accuracy, comparing them to conventional impression techniques [25]. These authors highlighted that while some IOS models showed relatively high accuracy, conventional impressions generally provided superior clarity of finish lines, particularly with challenging subgingival margins, underscoring the limitations IOS devices may face in complex preparations and suggesting a need for further technological advancements [25].

To date, there is insufficient scientific evidence regarding the accuracy levels of IOSs on tooth abutments with horizontal preparations at different depths below the free gingival margin. Additionally, there is a lack of data about the efficiency of IOSs in detecting the tooth's anatomical surface beyond the finish line. Some studies have reported that the deeper a crown margin is positioned, the more challenging it becomes to detect the finish line and over-preparation area [12,16,29]. Furthermore, scanning systems based on ultrasound technologies have been proposed to address this difficulty and make impressions of subgingival margins [30]. Regarding vertical preparation geometries, a recent study has demonstrated that it is possible to detect the surface beyond the finish area of this tooth preparation geometry [31]. Moreover, the accuracy values were within the clinically accepted threshold of 150 μm, and these values were comparable for both preparation depths at 1 and 2 mm below the free gingival margin [31].

The present research aims to assess the accuracy of an IOS (i700, Medit, Seoul, Korea) on models of tooth abutments prepared with horizontal designs at different depths of the finish line, 1 and 2 mm below the free gingival margin. It also seeks to evaluate if it is possible to detect a portion of the over-preparation area of the tooth beyond the finish margin at these preparation depths. The first null hypothesis posits no difference in the accuracies of scans made on tooth abutments with horizontal geometries at 1 and 2 mm below the gingival margin. The second null hypothesis states that it is not possible to detect the surface beyond the finish lines of the tested tooth abutments.

2. Materials and methods

2.1. Sample preparation

A single reference maxillary typodont (ANA-4 V CER, Frasaco GmbH, Tettnang, Germany) (Fig. 1A) representing a standard permanent dentition was utilized. The artificial teeth, made of ivorine, could be either removed from or fixed to the typodont through a screw-retained system.

Following the scanning of the typodont using a metrological scanner (Atos Core 80; GOM, Braunschweig, Germany), two detachable and screwable abutments were designed for the reference typodont using DentalCAD 3.0 Galway software (Exocad GmbH, Darmstadt, Germany) (Fig. 1B). These abutments were designed with horizontal preparation geometry featuring a 0.8 mm chamfer. Consequently, two digital abutments were generated, with the chamfer positioned at both 1 and 2 mm below the free gingival margin. This resulted in two digital reference abutments: horizontal −1 mm (H-1) and horizontal −2 mm (H-2).

To ensure consistent total occlusal convergence (TOC), a 5° angle was made to each opposing axial surface, resulting in an overall TOC of 10° This specific convergence angle was selected as it exhibited optimal values for prosthetic retention and reproducibility [32]. The width of the bottom of the gingival sulcus was maintained at 0.5 mm, and this distance was uniformly maintained along the entire intracrevicular portion of the test abutments. To maintain the measurements consistent when transitioning from 1 to 2 mm subgingivally, the abutments were vertically recessed in the apical direction, with the missing volume then added at the occlusal level in the −2 mm preparation. This adjustment aimed to extend the occlusal surface by 1 mm and minimize any alteration of the occlusal area to be scanned with the IOS.

The estimated change in the occlusal surface (ΔS) of the abutments, resulting from the sinking of the preparation margins from 1 to 2 mm subgingivally with a constant axial surface angulation of 5°, was determined using the following formula:

$$\Delta S = 1 - \frac{P tan\alpha}{R_1}$$

Here, P represents the depth of abutment sinking (1 mm), while α denotes the 5° axial angulation of the abutment. R_1 corresponds to the radius of the occlusal surface of the abutment with the margin positioned at 1 mm below the gingiva. A schematic illustration of ΔS is depicted in Fig. 2.

The designed reference abutments were manufactured using a 3D printer (Anycubic Photon S, Anycubic 3D Printing, Shenzhen, China) and UV Resin (Anycubic 3D Printing, Shenzhen, China) with a printing wavelength of 405 nm. An apical hole was incorporated into each abutment to facilitate screwing them onto the reference typodont. The printed abutments were kept for 24 h before scanning in a light-blocking

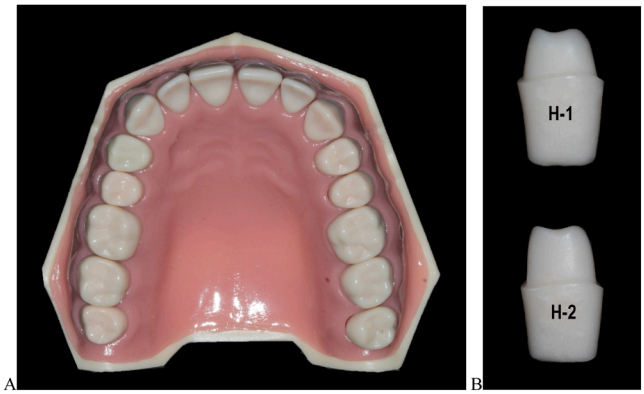

Fig. 1. A, Standard typodont for reference. B, 3D printed abutments: H-1, Horizontal −1 mm; H-2, Horizontal −2 mm.

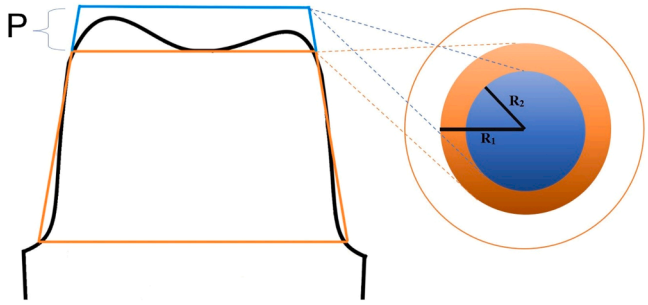

Fig. 2. Diagram illustrating the calculation of presumed occlusal surface variation (ΔS) with a 1 mm deepening of the abutment and a 5° axial angulation. P represents the depth of abutment (1 mm). R_1 is the radius of the occlusal surface of the abutment with a margin at 1 mm below the gingiva, and R_2 at 2 mm.

black box at 25 °C in a moisture-free environment.

The reference files consist of scans made of these printed abutments using an industrial white light metrology scanner (Atos Core 80; GOM). The scan settings for the reference files were as follows: working distance of 170 mm, point spacing of 30 μm, and measurement accuracy of ±2.5 μm.

2.2. Scanning procedure

For obtaining the experimental scans, the reference typodont underwent scanning using an IOS, specifically the Medit i700 (software Medit Link v2.5, Medit, Seoul, Korea). Prior to scanning, the IOS was calibrated, and ten non-experimental scans were conducted as tests and to allow the device to warm up. The scanning strategy recommended by the manufacturer was followed, starting from the occlusal surface of the right third molar and proceeding longitudinally to the contralateral one, then moving buccally and palatally. Upon completion of this scanning flow, the abutment was zoomed in to check for any gaps. If gaps were detected, the scan was resumed from the adjacent surfaces to fill them (Fig. 3). The high-resolution mode, with a scan depth set to 21 and "HD ON" and "no filter" mode activated, along with the reliability map, was utilized to scan the deepest area of the tooth abutment. Each scan was performed by an experienced prosthodontist (G.R.) on the same day, in the same room, under consistent lighting and climatic conditions: a temperature of 22 °C, an air pressure of 760 mmHg, a relative humidity of 45 %, and lighting at 1000 lux with a color temperature of 4400 K.

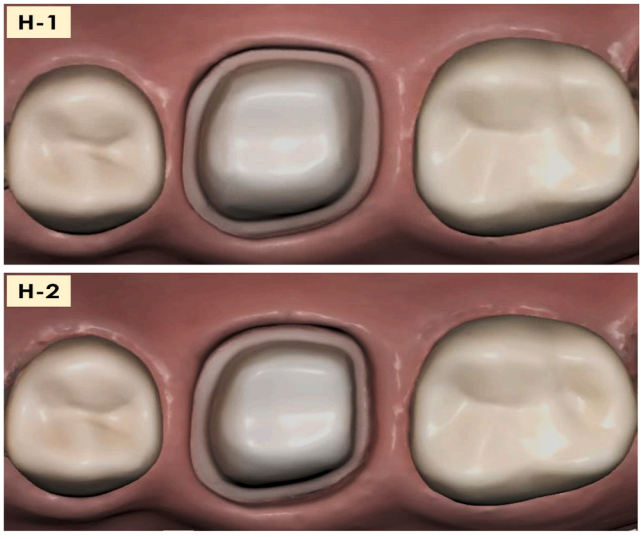

Fig. 3. Intraoral scans of each abutment. Medit i700 scans: H-1, Horizontal −1 mm; H-2, Horizontal −2 mm.

The scanning sequence was randomized using a random sequence generator (Random Number Generator Pro v.1.72, Segobit Software) to minimize operator fatigue effects and related bias. Additionally, a twelve-minute interval was provided between scans to allow for operator rest and proper cooling of the device. The number of shots per scan ranged from 1514 to 2546, and the time required for a complete arch scan varied between 1 and 2 min.

2.3. Three-dimensional analysis

All Standard Tessellation Language (STL) files obtained with the IOS were imported into specialized software (Meshlab v2016.12; ISTI-CNR) where each scan was sectioned to isolate the prepared abutment with its marginal geometry and the surface beyond it. Two experimental groups were created ($n = 10$), designated as "H-1″ for horizontal preparation at 1 mm below the gingival margin and "H-2″ at 2 mm. Both the reference scans and subsequently, the two sets of STL files ($n = 20$) were imported into Geomagic Control X (3D SYSTEMS, software v2018.0.1) (Fig. 4), and the accuracy of each was assessed by calculating trueness and precision, measured in μm. The two digital reference abutments were imported as "reference data" in the software. An "initial alignment" was conducted by the software, followed by a "best-fit alignment". After aligning the two digital models, the "3D compare" function was initiated. The parameters in the "color bar option" were set to max/min range = 0.5 mm and specific tolerance = ±0.15 mm. The SD value was chosen from the "tabular view-3D compare". This measure (SD) represents the mean between positive and negative deviations resulting from each superimposition of digital surfaces, as computed by Geomagic. Thus, the mean of the SD values was utilized to assess trueness and precision [4, 33]. This method generated a "color map" for visual inspection of the displacements between the surfaces of the overlapped digital models. As regards the whole abutment evaluation, the green areas indicated a minimum displacement of ±0.1 mm of the digital model compared to the "reference data"; conversely, the red and blue areas indicated outward and inward displacements respectively of +0.5 mm and −0.5 mm (Fig. 4). Instead, for the limited area of the margins, the set values were changed, in order to obtain a more detailed graphic map compared to the one of the entire abutment due to the clinical need for greater accuracy at the margins. To this end, the specific tolerance parameter, represented by the green color, was lowered to ±15 μm, while the extremes of the color map were narrowed to ±150 μm (Fig. 5). For each experimental group, trueness was evaluated as the mean of the SD values resulting from the superimposition between each experimental scan and the corresponding digital reference abutment. Precision was measured as the mean of the SD values for each experimental scan and the scan that achieved the best value of trueness after overlapping on the corresponding digital reference abutment in each of the 2 experimental

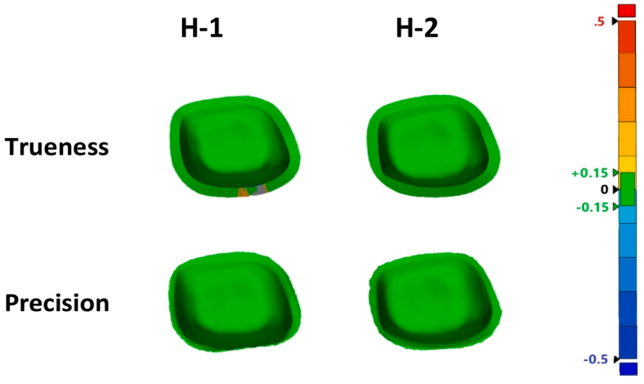

Fig. 4. Analysis of trueness and precision displaying the best alignment for each experimental scan. Green areas indicate minimal displacement of experimental scans compared to the reference model.

Fig. 5. Marginal trueness after the best-fit alignment. Green regions denote the least displacement of the experimental scans relative to the reference model.

groups. Consequently, the scans of the same group were overlapped on this selected scan, and the precision of each test group was measured as the mean of SD values registered by each of these overlaps [4,33].

2.4. Statistical analysis

Statistical analyses were conducted using specialized software (IBM SPSS v25; IBM). Descriptive statistics (e.g., mean, standard error, median, interquartile range, 95 % confidence interval) and additional calculations to assess the overall statistical significance of the differences between the groups (p=.05) were performed. Specifically, the Kolmogorov-Smirnov test was utilized to verify data normality. The independent sample test was employed to analyze differences between groups. A post hoc power analysis was conducted with G*Power (v. 3.1.9.7, Universität Kiel, Germany) to estimate the sample size effect. Approximate "Effect size d" conventions are large = 0.8, medium = 0.05, and small = 0.02. For the present analysis, a large effect size was estimated.

3. Results

There was a 79.94 % possibility of correctly rejecting the null hypothesis of no difference between H-1 and H-2, with 20 measurements for each experimental group, for a total of 20 assessments per abutment geometry.

The ΔS of the tested abutment geometry was 0.971 mm^2.

The descriptive statistics for trueness (C.I. 95 %) with upper-lower bounds, means, and standard errors are summarized in Table 1. The mean values were normally distributed for the 2 groups, as reported by the Kolmogorov-Smirnov test (p>.05), while the Levene test reported homogeneity of the variances (p=.909). The t-test for equality of mean was not significant for the comparison between the whole abutments: t(18)=2.072; p=.053; mean difference=1.660; standard error difference=0.801. Besides, The same test was not significant for the marginal areas: t(18)=6.546; p=.954; mean difference=19.280; standard error difference=2.945. As regards the analysis of precision, the descriptive statistics (C.I. 95 %) with upper-lower bounds, means, and standard errors are shown in Table 2. The mean values were normally distributed for all the groups, as reported by the Kolmogorov-Smirnov test (p>.05). The Levene test showed homogeneity of the variances (p=.857). The t-test for equality of mean between the whole abutments was significative: t(16)=5.161; p<.001; mean difference=11.544 standard error difference=2.237.

About the analysis of both the entire abutment and the marginal

Table 1
Descriptive statistics for trueness (μm) with 95 %-confidence intervals (CI95).

Intraoral Scanner System	Experimental Group	Area	Upper-Lower bound (95 % CI)	Mean	Standard Error
MEDIT i700	H-1	Whole abutment	39.7–42.4	41.1	.575
		Margin	57.5–68.0	62.7	2.314
	H-2	Whole abutment	38.2–40.7	39.4	.550
		Margin	39.9–47.6	43.5	1.821

H-1, Horizontal −1 mm; H-2, Horizontal −2 mm.

Table 2
Descriptive statistics for precision (μm) 95 %-confidence intervals (CI95).

Intraoral Scanner System	Experimental Group	Upper-Lower bound (95 % CI)	Mean	Standard Error
MEDIT i700	H-1	23.9–30.9	27.4	1.520
	H-2	12.1–19.6	15.9	1.640

H-1, Horizontal −1 mm; H-2, Horizontal −2 mm.

area, the color bar map of the best superimposition for each group of scans did not show outward and inward displacements greater than 150 μm (Figs. 4-5).

Figs. 3 and 4 show that the finish lines of horizontal preparations are visible both at 1 and 2 mm below the free gingival margin. Conversely, the surface area beyond the finish margins is not visible at both 1 and 2 mm subgingivally (Fig. 6 and Fig. 7).

4. Discussion

The present study aimed to compare the accuracy of an IOS (Medit i700) on models of tooth abutments prepared with horizontal finish geometries at both 1 and 2 mm under the free gingival margin. The first null hypothesis, stating that there is no difference within the accuracies of scans made on tooth abutments with the tested geometry at different depths, was rejected. Conversely, the second null hypothesis was accepted because the IOS was not able to detect the surface beyond the horizontal finish lines.

The descriptive statistics showed mean values of the accuracy of <150 μm for the tested geometry both at 1 and 2 mm below the gingival margin, such values were in the clinically accepted threshold for the IOS [34].

According to ISO-5725, the accuracy of a measurement method is defined by 2 parameters: "trueness" and "precision". "Trueness" indicates the closeness of agreement among the arithmetic mean of a large number of test results and the reference value; “precision” represents the closeness of agreement between intragroup data collected by repetitive measurements [35,36]. In other terms, trueness defines how a measurement matches the actual value while precision describes the consistency of repeated measurements. The trueness and precision values of the Medit i700 ranged between 38.2–42.4 μm and 12.1–30.9 μm respectively for the entire abutment evaluation; these values are comparable to those reported for the same IOS by Jivanescu et al. (trueness: 25.55 ± 1.85 μm; precision: 9.1 ± 3.8 μm) for short-span fixed dental prostheses [37] and to those reported in another study with vertical preparation geometries (trueness: 30.6–39.8 μm; precision: 8.2–32.5 μm) [31]. Similarly, the study by Bernauer et al. analyzing the accuracy of different scanners (Trios 3 and Primescan) on several preparation geometries, including the one tested in this study, showed comparable trueness values on this preparation geometry (0.8 mm chamfer) (Trios 3 trueness: 39 ± 4 μm on molars, Primescan trueness: 41 ± 5 μm). These values were similar to the present study despite the preparation depth tested by Bernauer et al. being epigingivally and not subgingivally [16]. Also noteworthy is the comparison between the present study and the one conducted by Nedelcu et al. [25]. Both studies highlight the limitations of IOS technology in capturing certain preparation designs, particularly below the gingival margin [25]. In the present study, the findings contribute to the field by showing that the Medit i700 scanner can achieve clinically acceptable accuracy in horizontal preparations, though with limitations in capturing areas beyond the finish line. Meanwhile, Nedelcu et al. offer a comparative perspective, suggesting that while some IOS devices perform well, traditional impressions remain more reliable in terms of detail accuracy, especially at the finish line [25].

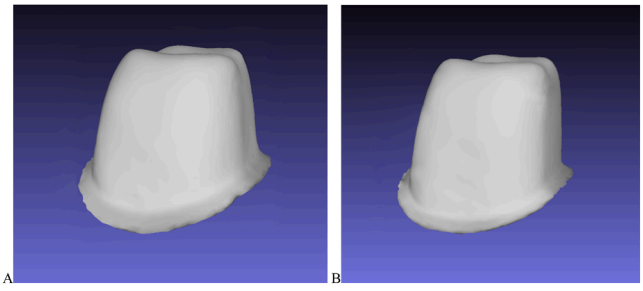

Fig. 6. Superimposed images demonstrating the inability to detect areas beyond horizontal preparation margins. A: H-1; B: H-2.

Fig. 7. Illustration depicting limitations of scanner light beam on surfaces beyond horizontal finish lines due to anatomical undercuts. Schematic representations of various angles of the IOS on horizontal margins are provided.

However, in the present study, the mean values of trueness for the specific marginal area are slightly increased compared to the area of the entire abutment (41.1 vs 62.7 at H-1, and 39.4 vs 43.5 at H-2). This shows that the accuracy at the margin is reduced, at least from what the descriptive analyses show. However, it is not possible to evaluate whether there are statistically significant differences between the margin and the entire abutment area, as the samples are different in terms of extension and morphology of the measured area. For this reason, the Authors intend to show the margin data with those of the entire abutment purely for descriptive purposes.

It is not possible to provide a range of values for the accuracy of IOS scans on a single tooth abutment, because of the heterogeneity and possible confounders of different research protocols used in the literature. Indeed, various IOS were examined, scans were performed by several operators on different reference models or environmental conditions, and various parameters were investigated, such as the root mean square, standard deviation, and mean absolute distance of the superimposed surfaces [16,25,38–40]. Nevertheless, a study with a research protocol similar to that shown in the present investigation was made by Lee et al. on a single molar abutment, reporting comparable trueness values in the range of 24–34.1 μm [41].

The surface beyond the finish line was not detectable for horizontal preparations. Due to their geometry, horizontal preparations do not allow the scanner light beam to pass easily beyond the finish line because of the presence of geometrical undercuts that can create possible shadow areas. According to previous studies, the angle of the scanner light beam is an important factor in detecting the surface beyond the finish area [25,29] as if there was too much angulation between the coronal-apical axis of the tooth and the light beam, then the gingiva itself would favor the formation of shadow cones. As regards the depth of tooth preparations, the tested IOS showed better results for deeper preparations. Moreover, significant differences reported that the precision of H-1 is worse than that of H-2 ($p < .001$). The presented results showed that the technology of Medit i700 (three-dimensional in-motion video technology and three-dimensional full-color streaming capture) is efficient with deep subgingival margins particularly [42].

To sum up, it appears that the preparation depth is a variable that affects the scanning accuracy in the case of horizontal preparations. Besides, it should be considered that the IOS achieved clinically acceptable values for both trueness and precision, showing its suitability for scanning these abutment geometries.

The present study had some limitations, primarily due to its in vitro nature; specifically, the experimental scans were made with only one IOS on resin models of tooth abutments, so, clinically relevant factors such as humidity, temperature, optical features, intraoral anatomic limitations, mobility and resilience of soft tissues were not factored.

Particularly, a proper clinical displacement of gingival tissues or particular anatomical conformation of every single tooth could influence the present results. Moreover, despite the presumed occlusal surface variation being numerically negligible, it was calculated on the morphology of a truncated cone, which does not reproduce the perfect morphology of the model abutments. Additionally, new versions of the IOS software and/or hardware may be available for purchase at the time of publication.

In order to corroborate the findings of the present investigation, further studies should be done, including clinical trials with larger sample sizes.

5. Conclusions

Based on the findings of this *in silico* comparative investigation using the Medit i700 intraoral scanner (IOS) on horizontal tooth preparations at depths of 1 and 2 mm below the free gingival margin, the following conclusions can be drawn:

- Tooth abutments with a detectable chamfer can be effectively scanned.
- The mean accuracy values fall within clinically accepted limits.
- The IOS does not clearly detect the surface beyond the finish line.
- Precision is higher at 2 mm depth compared to 1 mm.
- Trueness results are comparable between 1 mm and 2 mm depths.

Further in vitro and in vivo studies, as well as randomized controlled trials, are necessary to validate the outcomes of this in vitro investigation.

CRediT authorship contribution statement

Fernando Zarone: Writing – review & editing, Supervision, Project administration, Methodology, Formal analysis, Conceptualization. **Gennaro Ruggiero:** Writing – review & editing, Methodology, Formal analysis, Data curation, Conceptualization. **Lucio Lo Russo:** Supervision, Formal analysis. **Annamaria Mastrosimone:** Methodology, Formal analysis. **Roberto Sorrentino:** Writing – original draft, Visualization, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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