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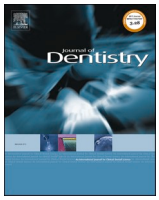

Trueness and precision of an intraoral scanner on abutments with subgingival vertical margins: An in vitro study

Roberto Sorrentino [a], Gennaro Ruggiero [a,*], Renato Leone [a], Edoardo Ferrari Cagidiaco [b], Maria Irene Di Mauro [a], Marco Ferrari [b], Fernando Zarone [a]

[a] Department of Neurosciences, Reproductive and Odontostomatological Sciences, Division of Prosthodontics, Scientific Unit of Digital Dentistry, University "Federico II" of Naples, Naples 80131, Italy
[b] Department of Prosthodontics and Dental Materials, School of Dentistry, University of Siena, Siena 53100, Italy

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ABSTRACT

Objectives: This study aimed to evaluate the accuracy of an intraoral scanner (IOS - Medit i700) on tooth abutments with vertical preparations at 2 depths below the free gingival margin, and to determine if the IOS can reproduce the area beyond the finish surface of the tested preparation geometry.
Methods: Two abutments for a maxillary first molar were designed by means of CAD software, with vertical preparations set at 1 and 2 mm below the gingiva. These abutments were subsequently printed in resin and placed on a reference model. The reference files consisted of scans made using a metrological machine on these abutments. Ten scans were made with the tested IOS on each sample, resulting in two study groups. The scans from the experimental groups were labeled "V-1″ for vertical preparation at 1 mm below the gingival margin and "V-2″ for 2 mm below.
The analysis of these scans was performed using Geomagic Control X (3D SYSTEMS) to assess their trueness and precision in μm. Descriptive statistics with a 95 % confidence interval were employed, alongside independent sample tests, to ascertain any differences between the groups (α=0.05).
Results: Statistically significant differences were not found both for trueness (p=.104) and precision (p=.409), between the tested geometries. The mean values for trueness were V-1 = 37.5[31.4–43.6]; V-2 = 32.6 [30.6–34.6]. About the precision, the mean values were V-1 = 20.5[8.4–32.5]; V-2 = 18.4[8.2–28.5]. In both the study groups, it was possible to detect the surface beyond the finish area.
Conclusions: Within the limitations of this study, vertical preparation design allows for registration of the tooth anatomy beyond the finish area with IOS. Moreover, the mean accuracy values were clinically acceptable at both 1 and 2 mm below the gingival margin.

Clinical significance

Tooth abutments with vertical finishing areas until 2 mm below the gingival margin could be scanned.

1. Introduction

Over the past few decades, the integration of digital technology in Dentistry, together with the development of more advanced and attractive restorative materials, has led to a significant shift in prosthodontic practices.

In Prosthodontics, the latest IOSs provide clinically acceptable accuracy for both tooth- and implant-supported restorations [1,2] regardless of abutment geometry [3–5]. However, a challenge is the difficulty in detecting anatomical information when the finish line of tooth abutments is positioned deep in the gingival sulcus [6].

In the Glossary of Prosthodontics Terms, the "finish line" or "margin" of an abutment is defined as "the junction of prepared and unprepared tooth structure with the margin of a restorative material" [7]. In the case of pure vertical preparations, also known as feather edge, the terminology of finish "area" and not finish line must be used, as a real line does

* Corresponding author.
E-mail address: gennaro.ruggiero2@unina.it (G. Ruggiero).

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not exist and therefore it is not visible; indeed, after impression making, the prosthetic margin will be marked on the preparation area reproduced on the master cast [8]. Vertical preparations are mainly indicated on stabilized teeth with periodontal disease, but they could be used for any tooth as they are more conservative than horizontal ones for the same height of the prosthetic margin, preserving dental tissue. Additionally, the vertical geometry is recommended when it is important to extend the prosthetically useful region in order to achieve better retention and stability as well as to mask the crown margin below the gingiva [9]

It is crucial to record accurately the marginal anatomy in both conventional impressions and digital scans to ensure a proper fit of restorations [10], and to provide dental laboratories with important information about tooth contour [11].

Studies have shown that IOSs provide better detection of supragingival finish designs than epigingivally located ones [12], but results can be affected by factors that obscure the apical portion of the preparation, such as nearby teeth or marginal gingiva [13]. Differently, conventional impression materials can penetrate deeper into the gingival sulcus to detect apical details because of their rheological properties [14], especially when a 2-step impression technique is used, since the medium- or heavy-body material pushes the light-body paste into the gingival sulcus [15], displacing the gingiva laterally and apically during the material setting [16]. This allows conventional elastomeric impression materials for a viable solution to record both the subgingival finish area and an apical portion of unprepared tooth anatomy beyond it.

There are many studies in the literature comparing the use of digital scans with traditional impressions, on completely edentulous ridges [17], natural teeth [2,18], and implant abutments [1,19], in which IOSs reported better results in terms of trueness and precision. Furthermore, different scanning strategies [20], and IOS devices available on the market were compared [21,22].

As regards the vertical geometries, numerous clinical studies exist in the literature, covering both crowns [23,24], and partial restorations such as veneers [25]. For instance, Imburgia et al. suggest that lithium disilicate veneers with feather-edge margins exhibit clinical effectiveness comparable to outcomes reported for alternative margin designs and various types of restorations [25]. Mandelli et al. demonstrated that inverted impression scanning in their clinical cases was capable of capturing deeper margins compared to regular intraoral scanning, thereby highlighting the advantages and potential of this method [23]. Besides, Mangano et al. employed a similar technique for 30 single zirconia crowns, reporting satisfactory outcomes [24].

Currently, there is limited research on the accuracy of IOSs on tooth abutments with vertical designs, at different depths below the gingival margin, and on the ability of IOSs to detect tooth anatomy beyond the finish area. Some *in vitro* [12] and *in vivo* [6,26] studies showed that the deeper a restoration margin is placed, the more difficult is to detect the finish line/area and the surface beyond it [6,12,26]. Besides, several studies have suggested that scanning systems based on ultrasound technologies may be used to solve this difficulty and make impressions of subgingival margins [27].

The current research aims to evaluate the accuracy of an IOS (i700, Medit, Seoul, Korea) on models of tooth abutments prepared with vertical designs at 1 and 2 mm below the gingival margin, and to determine if it is possible to detect a portion of the unprepared surface beyond the finish area.

The first null hypothesis was that there is no difference within the accuracies of scans made on tooth abutments with vertical geometry at 1 and 2 mm below the gingival margin.

The second null hypothesis stated that it is not possible to detect the surface beyond the finish areas of the experimental tooth abutments.

2. Materials and methods

2.1. Sample preparation

A maxillary typodont (ANA-4 V CER, Frasaco GmbH, Tettnang, Germany) (Figs. 1, 2A) with artificial ivorine teeth, which can be fixed with a screwing system to the typodont, was scanned with an industrial metrological scanning machine (Atos Core 80; GOM). Two removable and screwable abutments were then designed for the typodont using DentalCAD 3.0 Galway software (Exocad GmbH, Darmstadt, Germany) (Fig. 2B). The experimental abutments (V-1 and V-2) were made with vertical edgeless design. The preparation areas were placed 1 mm from the sulcus bottom, in the case of the preparation with the boundary at 2 mm below the gingiva, and 2 mm from the bottom for the preparation at 1 mm, considering a sulcus drawn with a depth of 3 mm. Two experimental groups were made ($n = 10$): they were named "V-1″ for vertical preparation at 1 mm and "V-2″ for the same at 2 mm. The abutments were designed with a 5° angle of each opposing axial surface, resulting in an overall total occlusal convergence (TOC) of 10°, as such convergence angle value was reported to provide the best retention and reproducibility for prosthetic restorations [28]. The distance between the axial surface and the col of the papilla was 1.2 mm and progressively decreased along the intrasulcular space in the apical direction until the bottom of the sulcus and the root surface of the test abutments were in contact (Fig. 2B). In order to keep the aforementioned measurements constant while going from 1 to 2 mm subgingival, the abutments were sunk vertically in the apical direction, then adding that missing volume at the occlusal level in the −2 mm preparation, in order to extend the occlusal surface of 1 mm and reduce any possible modification of the occlusal area to be scanned with the IOS.

The presumed occlusal surface variation (ΔS) of the abutments when the preparation margins were sunk from 1 to 2 mm below the gingiva, at a constant axial surface angulation of 5°, was calculated with the following equation:

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

P is the measure of the abutment deepening (1 mm) while α is the 5° axial angulation of the abutment. R_1 is the radius of the occlusal surface of the abutment with the margin at 1 mm subgingivally. A schematic representation of ΔS is shown in Fig. 3.

The designed reference abutments were printed with a 3D printer (Anycubic Photon S, Anycubic 3D Printing, Shenzhen, China) and UV Resin (Anycubic 3D Printing, Shenzhen, China) using a printing wavelength of 405 nm. The printed abutments were stored for 24 h before scanning, in a black box that did not allow the passage of light, at a temperature of 25 °C in a humidity-free environment.

The reference files are scans made on these printed abutments by using an industrial structured white light metrology scanner (Atos Core 80; GOM). The following settings have been set for the reference file scans: working distance: 170 mm, point spacing: 30 μm, measure accuracy: ±2.5 μm.

2.2. Scanning procedure

The experimental scans were made by scanning the reference typodont with an IOS, Medit i700 (software version Medit Link 2.5, Medit, Seoul, Korea). The instructions for IOS calibration were followed before starting to scan, and 10 scans were made as a test and to warm up the device. The scanning strategy started from the occlusal surface of the right third molar and continued up to the contralateral one, moving then buccally and finally palatally. At the end of this scanning flow, it was zoomed on the abutment to check if there were any gaps. If so, the scan would have been resumed from the surfaces adjacent to the gaps, in order to fill them (Fig. 4). The high-resolution mode was selected to scan the deepest area of the tooth abutment; in particular, the scan depth was

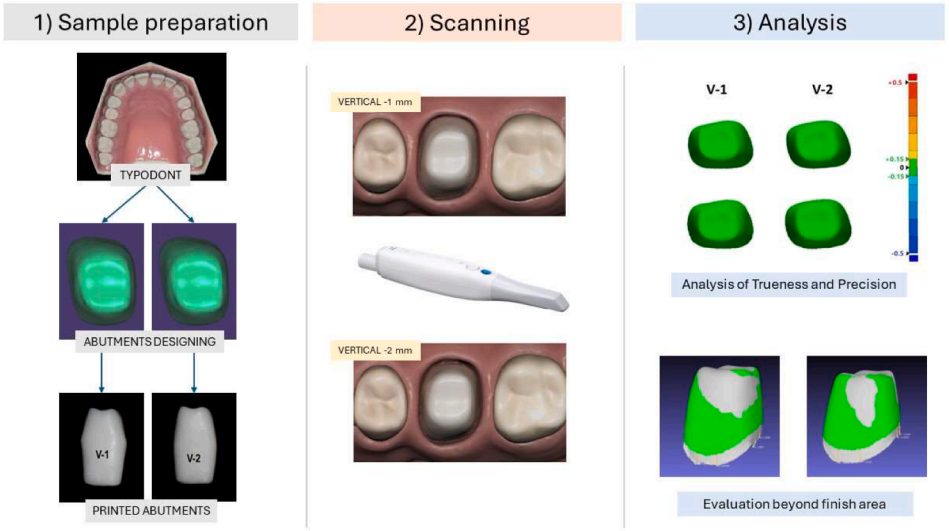

Fig. 1. Study design. Sample preparation, scanning of the abutments, and three-dimensional analysis.

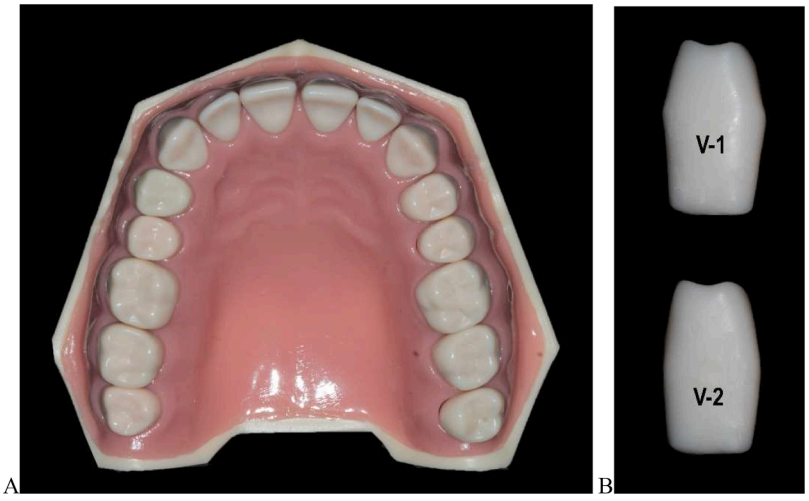

Fig. 2. A, Reference typodont. B, printed abutments: V-1, Vertical −1 mm; V-2, Vertical −2 mm.

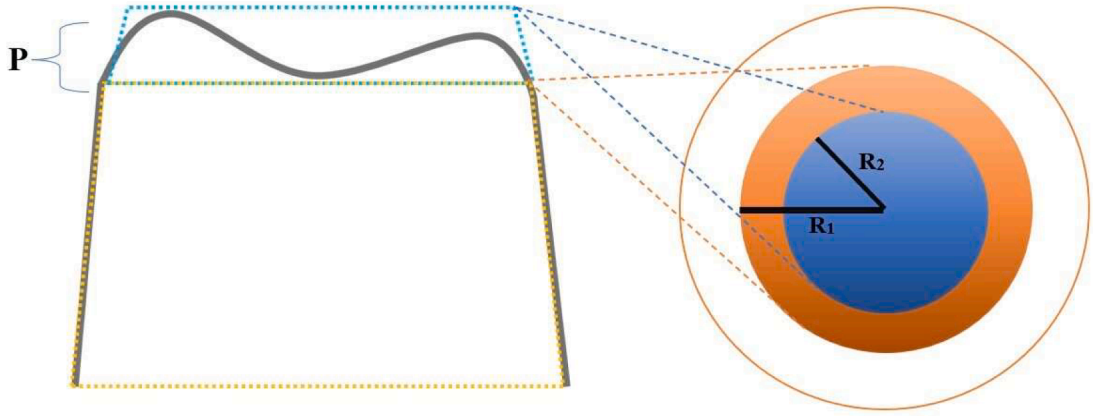

Fig. 3. Diagram for determining the presumed occlusal surface variation (ΔS) with 1 mm deepening of the abutment and 5° axial angulation. P represents the measurement of the abutment's depth (1 mm), R_1 represents the radius of the occlusal surface of the abutment with the margin located 1 mm below the gingiva, and R_2 represents the radius of the occlusal surface of the abutment with the margin located 2 mm below the gingiva.

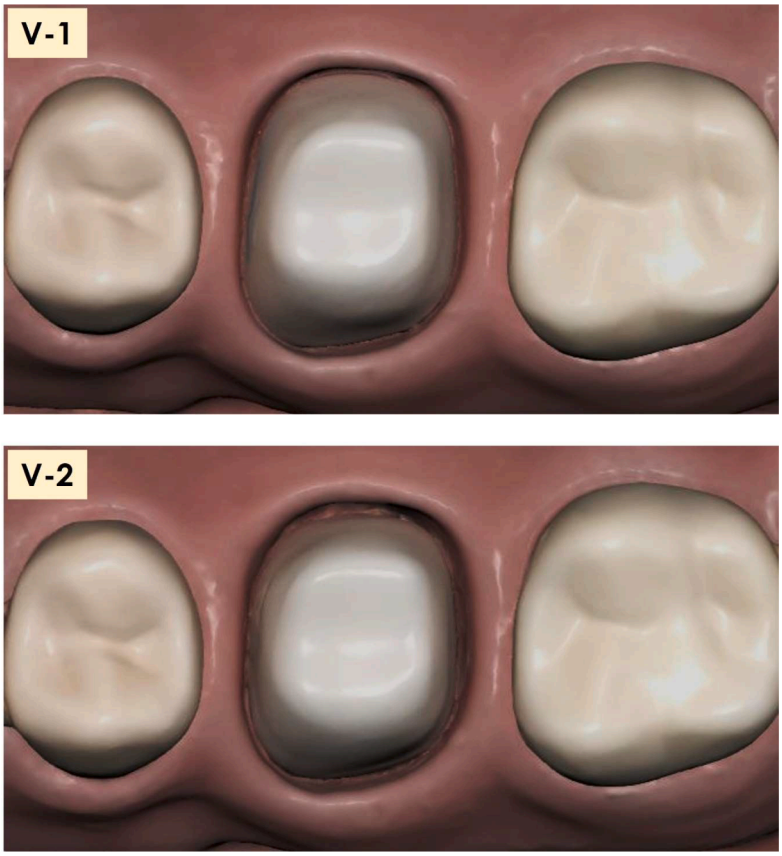

Fig. 4. IOS scans of the tested abutment teeth for vertical preparation geometry. V-1, scan on preparation 1 mm below the gingiva; V-2, 2 mm below the gingiva.

set to 21 with "HD ON", "no filter" mode and activation of reliability map.

Each scan was performed by the same prosthodontist, under similar lighting and environmental conditions, with a temperature of 22 °C, air pressure of 760 mmHg, and 45 % relative humidity. The scanning sequence was randomized with a random sequence generator (Random Number Generator Pro-v.1.72, Segobit Software) to reduce the effects of operator fatigue and prevent bias, with a 12 min interval between scans. The number of shots per scan varied between 1467 and 2234, and the time for a complete arch scan was between 1 and 2 min.

2.3. Three-dimensional analysis

The STL (Standard Tessellation Language) files were imported into a dedicated software (Meshlab v2016.12; ISTI-CNR), where each scan was cut to isolate the prepared abutment with its marginal geometry and the surface beyond it.

Both the digital reference abutments and the experimental scans were imported into Geomagic Control X (3D SYSTEMS, software v2018.0.1) (Fig. 5) and the accuracy of each scan was evaluated by calculating trueness and precision, measured in μm. The 2 digital reference abutments were imported as "reference data" in the software.

The software first performed an "initial alignment" followed by a "best fit alignment". After aligning the 2 digital models, the "3D compare" function was activated. The parameters for the "color bar option" were set to a max/min range of 0.5 mm and a specific tolerance of ±0.15 mm. The SD measure was selected from the "tabular view-3D compare" to measure trueness and precision. This measure is a mean between positive and negative deviations resulting from each superimposition of digital surfaces, as calculated by Geomagic. In particular, SD is used to measure the spread of the data around the mean. For this reason, the mean of the SD values was selected to measure trueness and precision [29].

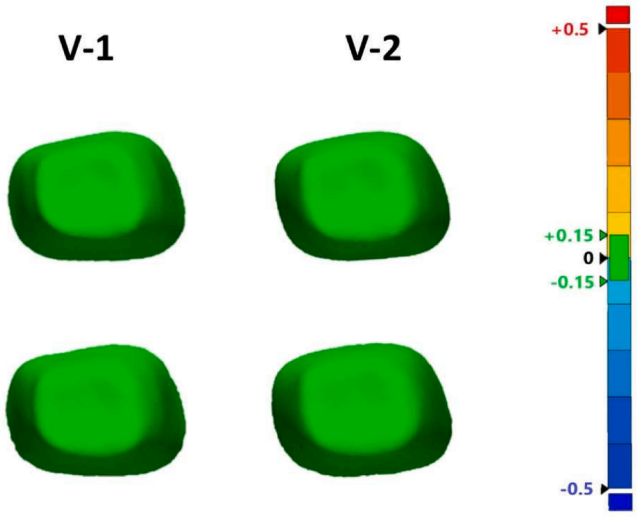

Fig. 5. Three-dimensional analysis of trueness and precision. The best alignment for each experimental scan. The green areas show the least amount of displacement in the experimental scan compared to the reference model.

A "color map" was generated for visual examination of the displacements between the surfaces of the overlapped digital models, with green areas indicating a minimum displacement of ±0.1 mm of the digital model compared to the "reference data" and red and blue areas indicating outward and inward displacements, respectively of +1.0 mm and −1.0 mm (Fig. 5).

In accordance with ISO-5725, the accuracy of a measurement system

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 [30]. Therefore, trueness represents how a measurement matches the actual value while precision defines the consistency of repeated measurements.

For each experimental group, the trueness was evaluated as the mean of the SD values resulting from the superimposition between each experimental scan and the corresponding digital reference abutment.

The precision of the experimental scans was evaluated by comparing the mean of the SD values for each scan to the scan that had the best trueness when overlapped with the corresponding digital reference abutment in the 2 experimental groups. The precision of each group was then determined as the mean of the SD values obtained from these overlaps [29].

The statistical analysis was done using dedicated statistical software (SPSS v25, IBM, Armoni, NY, USA) and included the use of descriptive statistics, such as mean, standard error, median, interquartile range and 95 % confidence interval, and other calculations to evaluate the overall statistical significance of the differences between the groups (p=.05). In particular, the Kolmogorov-Smirnov test was used to check for normality of the data. The independent sample test was conducted to examine the differences between the groups.

Moreover, a post-hoc power analysis was performed using G*Power software (v. 3.1.9.7, Universität Düsseldorf, Germany) to determine the sample size effect. The approximate conventions for "Effect size d" are large = 0.8, medium = 0.05, and small = 0.02. The analysis resulted in an estimated large effect size.

3. Results

There was a 53.04 % possibility of correctly rejecting the null hypothesis of no difference between V-1 and V-2, with 10 measurements for each experimental group, for a total of 20 assessments per abutment geometry (Fig. 6).

The ΔS of the vertical preparations was 0.968 mm^2.

The descriptive statistics for trueness (C.I. 95 %) with upper-lower bounds, means, and standard errors are summarized in Table 1 and shown in Fig. 7.

The mean values were not normally distributed for the 2 groups, as reported by the Kolmogorov-Smirnov test ($p < .05$), while the Levene test exhibited no homogeneity of the variances ($p = .011$). The t-test for equality of mean was not significative: t(18) = 8.063; $p = .104$; mean difference = 4.570; standard error difference = 2.570.

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 and displayed in Fig. 8.

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

Intraoral scanning system	Experimental Group	Upper-Lower bound (95 % CI)	Mean	Standard Error	Minimum-Maximum
MEDIT i700	V-1	31.4–43.6	37.5	2.632	31.4–54.0
	V-2	30.6–34.6	32.6	.874	30.3–39.0

The mean values were not normally distributed for all the groups, as reported by the Kolmogorov-Smirnov test ($p < .05$), while the Levene test showed homogeneity of the variances ($p = .153$) The t-test for equality of mean was not significative: t(16) = 2.248; $p = .409$; mean difference = 6.544 standard error difference = 7.711.

Regarding the analysis of trueness and precision, the color bar map of the best superimposition for each group of scans did not show outward and inward displacements greater than 150 μm (Fig. 5).

The surface beyond the selected finish area was visible at both 1 and 2 mm subgingivally (Fig. 9). Moreover, there were marginal areas of the abutment not registered by the scanner when the light beam emitted by the IOS was not parallel to the long axis of the abutment, due to the presence of marginal gingiva, which did not allow the passage of the light beam, creating an undercut (Fig. 10).

4. Discussion

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 accepted. Conversely, the second null hypothesis was rejected because the IOS was able to detect the surface beyond the set vertical finish area.

The results of the study showed that for each tested preparation geometry the mean accuracy of the IOS was within the clinically acceptable threshold of 150 μm, an established misfit value for prosthetic rehabilitations [31]. Additionally, the trueness and precision values were found to be similar to those reported in previous research on the same IOS [32]. Specifically, the trueness values ranged from 30.6 to 39.8 μm, while the precision values ranged from 8.2 to 32.5 μm. This is consistent with the results reported by Jivanescu et al. for short-span fixed dental prostheses, with trueness values of 25.55 ± 1.85 μm and precision values of 9.1 ± 3.8 μm [32].

It is challenging to establish a specific range for the accuracy of IOS scans on a single tooth abutment due to the variety of research protocols used in previous studies [12,21,33,34]. This includes the use of different IOS, operators, reference models and environmental conditions, as well as the examination of various parameters (e.g., root mean square,

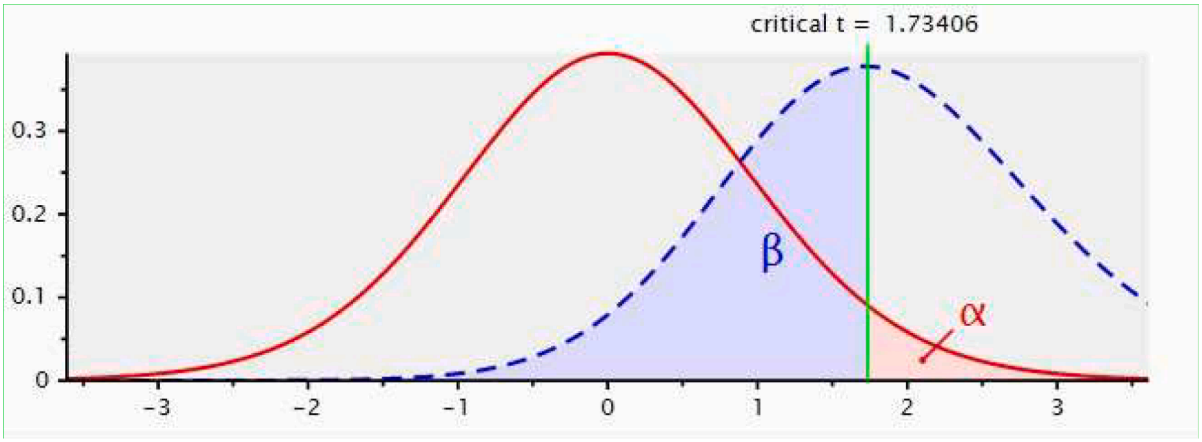

Fig. 6. Evaluation of the sample size effect: Power analysis.

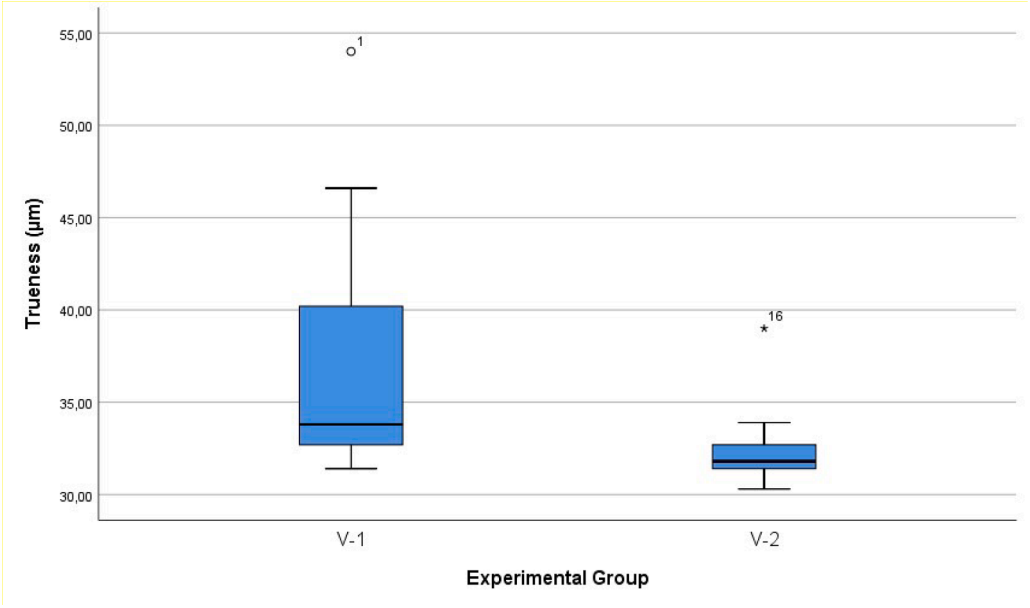

Fig. 7. Box plot chart of the descriptive statistics of trueness. The lines above and below the boxes indicate the minimum and maximum values, while the boxes show the range from the first quartile to the third quartile. The median value is represented by the line inside the box. Any possible outliers are shown as unfilled circles.

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

Intraoral scanning system	Experimental Group	Upper-Lower bound (95 % CI)	Mean	Standard Error	Minimum-Maximum
MEDIT i700	V-1	8.4–32.5	20.5	5.11	7.0–60.4
	V-2	8.2–28.5	18.4	4.416	9.8–52.3

standard deviation, and mean absolute distance), making it hard to compare results [12,21,33,34].

However, a study that used a research protocol similar to the current one was conducted by Lee et al. [35] on a single molar abutment and reported comparable trueness values within a range of 24–34.1 µm [35].

The area beyond the finish area was visible in the scans of the tested vertical preparations. It should be noted that the finish margin in these preparations was set arbitrarily as it is not possible to have an actual and visible finish "line" with a pure vertical preparation, therefore it is more correct to name it "finish area". The explanation for the possibility of detecting the area beyond the finish area, in vertical preparations, is related to the presence of anatomical undercuts. Due to their geometry, vertical preparations allow the scanner light beam to pass easily beyond the finish area for the absence of geometrical undercuts that could create shadow areas. Previous studies have shown that the angle at which the scanner light beam hits the surface is crucial for detecting the area beyond the finish line [22,26]. If the angle between the coronal-apical axis of the tooth and the light beam is too wide, then shadow cones will be created due to the interference of the gingiva along the direction of the light.

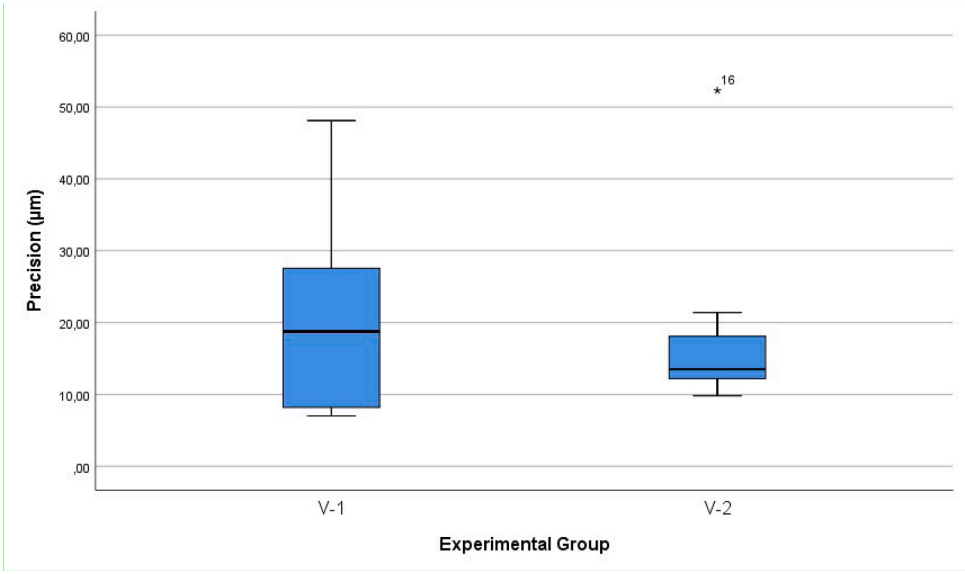

Fig. 8. Box plot chart of the descriptive statistics of precision. The lines above and below the boxes indicate the minimum and maximum values, while the boxes show the range from the first quartile to the third quartile. The median value is represented by the line inside the box. Any possible outliers are shown as unfilled circles.

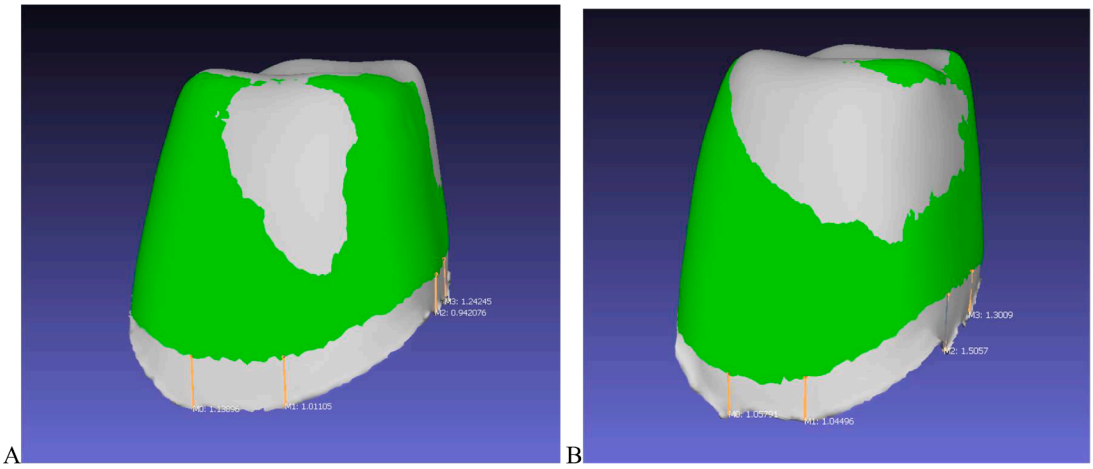

Fig. 9. Detection of the area over the selected finish margin with vertical preparations at 1 and 2 mm below the free gingival margin. A, V-1; B, V-2. The displayed segments show some linear measurements between the apical line detected by IOS and the set finish margin cut for the three-dimensional analysis.

Fig. 10. Representative schematizations of different angulations of the IOS light beam on vertical preparations. Different angles of the light beam and possible anatomical undercuts are related to the presence or absence of shadow cones.

The study found that the Medit i700 intraoral scanner had slightly better results for deeper tooth preparations. However, these differences were not statistically significant for trueness ($p = .104$) and precision ($p = .409$). The results of the study suggest that the Medit i700 technology, which uses 3D in-motion video technology and 3D full-color streaming capture, is effective for capturing deep subgingival geometries of tooth preparations. Additionally, it is worth noticing that the Medit i700 may be appropriate in capturing vertical preparations, due to the presence of a 45-degree angled mirror; this angulation allows for a more perpendicular reflection of light from the surface of a vertical preparation as compared to a horizontal marginal geometry. As a result, the software does not need to drastically adjust the image captured by the sensor, leading to a reduction in cumulative errors for its algorithm.

Finally, the tested intraoral scanner demonstrated clinically acceptable values for both trueness and precision, indicating its effectiveness in scanning tooth abutment geometries.

This study had some limitations, primarily due to its *in vitro* design with only one IOS tested. Specifically, the scans were performed on resin models of tooth abutments, so factors such as humidity, temperature, intraoral anatomy (space), and the movement and flexibility of soft tissues were not taken into account. Additionally, factors such as gingival displacement, intraoral fluids (e.g., crevicular and blood), or tooth anatomy may affect the results. Also, the study assumed that the occlusal surface variations were numerically insignificant, but it was calculated on the shape of a truncated cone, which may not accurately represent the morphology of the actual abutments. Moreover, the present study design does not analyze details on the marginal accuracy but only the overall value of the tested abutments.

In order to corroborate the findings of the present investigation, further studies should be done, including a larger sample size and aimed to investigate the geometries of tooth preparations in the marginal area specifically.

5. Conclusions

Within the limits of the current *in vitro* study, and considering the results derived from the scans conducted using the tested IOS (Medit i700) on tooth abutments with vertical geometries at both 1 and 2 mm below the free gingival margin, the following conclusions can be inferred:

- it is possible to detect the surface beyond the finish area of this tooth preparation geometry;
- the accuracy values were within the clinically accepted threshold;
- the accuracy was comparable for both preparation depths.

However, further *in vitro* and *in vivo* studies and randomized controlled trials are needed to confirm these findings.

CRediT authorship contribution statement

Roberto Sorrentino: Writing – original draft, Investigation, Data curation. **Gennaro Ruggiero:** Writing – review & editing, Methodology, Conceptualization. **Renato Leone:** Methodology, Formal analysis. **Edoardo Ferrari Cagidiaco:** Supervision, Formal analysis. **Maria Irene Di Mauro:** Supervision, Conceptualization. **Marco Ferrari:** Visualization, Formal analysis. **Fernando Zarone:** Writing – review & editing, Supervision, Project administration, Methodology.

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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