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Original Article

Comparative Accuracy of Digital and Conventional Impression Techniques for Implant-Supported Restorations: An In Vitro Analysis

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Abstract

The Purpose Of This In Vitro Research Was To Assess The Accuracy Of Intraoral Scans Acquired With The Trios 3shape® (3shape Trios, Copenhagen, Denmark) And Carestream Cs 3600™ (Carestream Dental, Stuttgart, Germany) Devices, Measured Against Conventional Polyvinyl Siloxane (Pvs) Impressions. The Reference Standard Employed Was A Laboratory Scanner. The Study Was Constructed Around 3d-Printed Master Models Reproduced From Partially Edentulous Clinical Cases Formerly Treated At Our Department (2017–2022)—All Cases Required At Least 2 Implants. Statistical Evaluation Was Conducted Using One-Way Anova And Two-Sample Z-Tests (A = 0.05) To Assess Mean Deviations And Variability. All Techniques Achieved High Accuracy, With Deviations From The Reference Point Of Less Than 30 Mm. The Digital Intraoral Scanners (Trios 3shape® And Carestream Cs 3600®) Exhibited Superior Accuracy Compared With Pvs Analog Impressions, With No Statistically Significant Difference Between The Two Ios Devices. Within The Constraints Of This In Vitro Study, Clinically Acceptable Accuracy Was Achieved By Both Ios Systems And Pvs Analog Impressions Alike. The Digital Systems Yielded Improved Performance In Terms Of Mean Deviation And Consistency. The Greater Accuracy And Consistency Of Digital Impressions May Improve Clinical Efficiency And Prosthetic Fit In Implant Rehabilitations. From A Clinical Perspective, These In Vitro Data Suggest That Digital Impressions Could Improve Prosthetic Fit And Workflow Efficiency, Though Additional In Vivo Corroboration Is Warranted. Clinical Significance: This Investigation Supports The Reliability Of Intraoral Scanning Compared With Conventional Impressions In Implant-Supported Rehabilitations. By Evidencing Strong Intrinsic Accuracy, These Results Contribute To Streamlining Digital Workflows In Implant Dentistry And Bolster The Promise Of Intraoral Scanning Within Static Computer-Guided, Flapless Implant Surgery. Neither Ethical Approval Nor Trial Registration Was Required For The Current In Vitro Inquiry, As No Patients Were Directly Involved During The Experimental Stage. The Digital Data Used To Fabricate The Laboratory Master Models Were Derived From A Separate Clinical Study Conducted At Asst Santi Paolo E Carlo, Milan (Ethics Committee Approval No. 1361, 12 July 2017; Clinicaltrials.Gov Registration, Unique Protocol Id 1361).

Keywords: Digital dentistry, Cad/cam dentistry, Implant restorations, Dental scanner, Intraoral digital impression

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Introduction

Over the past few decades, the dental field has undergone a shift driven by advances in digital technology. Digitalization is fundamentally reshaping the way clinicians deliver patient care and plan, carry out, and evaluate dental interventions. This digital shift has yielded numerous patient benefits, boosting diagnostic precision, fine-tuning treatments, and making the chairside experience more agreeable [1, 2].

A key early move toward digitalization was the rollout of Cone Beam Computed Tomography (CBCT), which enabled the capture of highly accurate three-dimensional radiographic imagery while substantially reducing patients' radiation dosage. Still, it would be narrow to view CBCT exclusively as a diagnostic adjunct. When obtained, it ought to be regarded as a portal into the CAD/CAM ecosystem. The arrival of CAD/CAM systems within dentistry has fundamentally reworked the design and manufacturing trajectories of prosthetic appliances. Following the capture of the patient's impression—whether digitally or via a traditional analog route later converted by laboratory scanners—the practitioner can use CAD software to design the prosthetic pieces. The blueprint can subsequently be relayed straight to a 3D printer or milling unit, enabling the swift fabrication of bespoke appliances. This modernized pathway can sidestep the cumulative inaccuracies commonly inherent in the protracted workflows of traditional methods [3, 4].

The full digitalization of the CAD/CAM production chain was ultimately completed by the introduction of intraoral scanners (IOS). These instruments have drastically reduced the time required for impression recording and have made exchanges with the dental laboratory far more rapid and streamlined [5, 6].

Notwithstanding the notable technological strides and increasingly encouraging clinical outcomes delivered by digital workflows, the scientific literature has cast doubt on the distinctions between traditional analog methods and their digital counterparts. However, the present evidence base remains divided on the accuracy (trueness and precision) of digital versus conventional impression modalities for implant-supported rehabilitations. Multiple studies and reviews document high or on-par accuracy of IOS against PVS across numerous clinical/in vitro contexts [7-9]. In contrast, other inquiries underscore shortcomings in full-arch or multi-implant spans (e.g., cumulative stitching and strategy-dependent errors), at times tilting toward conventional techniques for expansive spans [10-12]. Moreover, direct, side-by-side evaluations involving distinct IOS platforms and conventional PVS under uniform conditions remain sparse; notably, data comparing Trios3Shape® and Carestream CS 3600™—two widely embraced scanners built on different capture technologies—are scarce, even though some in vitro findings are available [13, 14].

Within this in vitro experimental design, intraoral scanners (IOS) are weighed against the prevailing benchmark for impression capture: traditional analog impressions.

The present study aimed to gauge the accuracy of the Trios3shape® and Carestream CS 3600TM intraoral scanners, as well as that of the traditional analog impression using polyvinyl siloxane (PVS). The impressions and scans were sourced from various implant cases managed prospectively. The null hypothesis holds that there are no meaningful differences in accuracy among the disparate impression methods.

Materials and Methods

Fifty-one master models, sourced from partial-edentulous cases previously handled at the University of Milan's Implantology and Prosthodontics Department, formed the basis of this laboratory investigation. Under consistent bench-top conditions, traditional and optical impression methods were compared. The master models were constructed from digital patient datasets (CBCT and intraoral scanning records), yet the actual experimental procedures involved no direct patient contact; consequently, this in vitro work fell outside the scope of requirements for ethical clearance or participant consent.

Given the study's exclusively bench-top nature and the absence of human subjects in the experimental segment, ethical review board approval and prospective trial registration were not required. The source files used to fabricate the laboratory master models were drawn from an earlier independent clinical study conducted at ASST Santi Paolo e Carlo, Milan (Ethics Committee approval no. 1361, dated 12 July 2017; ClinicalTrials.gov registration under Unique Protocol ID 1361). The work conforms to STROBE recommendations (https://www.equator-network.org/reporting-guidelines/strobe/) (last accessed 7 July 2023), and the Trend statement checklist was fully satisfied [15].

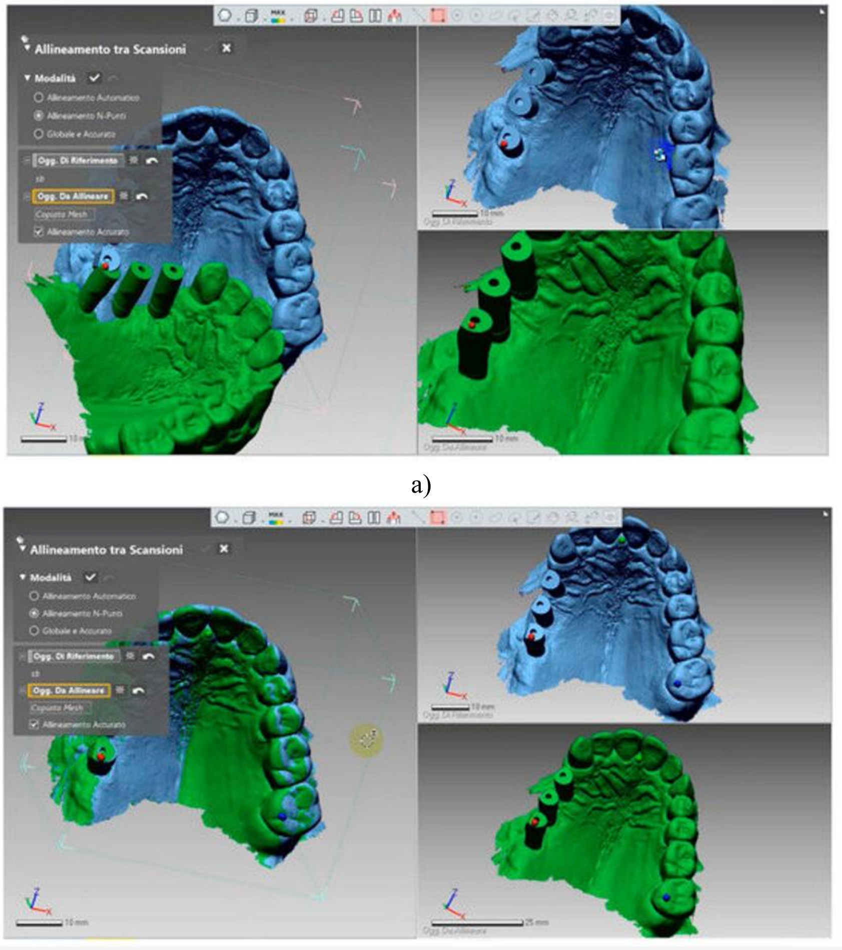
In vitro workflow

Before each Trios3shape® acquisition, implant scan bodies were mounted onto the printed master model. A polycarbonate replica was produced, and corresponding implant analogs were embedded within the master cast.

All measurements took the master model as their origin; altogether, four separate scans were performed per model. The study progresses entirely outside the realm of patient treatment, reflecting its in vitro nature from start to finish. Throughout the scanning process, the individual operating the equipment was informed of which specific device was in use at every stage. No element of concealment was introduced for either the scanner operator or the assessor of outcomes. The full set of enrolled casts was carried through to analysis; no data points were missing. The predetermined protocol was executed without any departures. The bench-top design inherently eliminates the risk of adverse incidents or unintended consequences.

1. Reference image: With scan bodies tightened onto the master model, the Concept Scan Top™ laboratory scanner was deployed to capture the reference dataset.
2. Trios3shape® image: With scan bodies re-secured, the Trios3shape® device was used to record the second dataset.
3. Carestream CS 3600™ image: With scan bodies positioned as before, the third collection was performed with the Carestream CS 3600™ unit.
4. Analog transfer copings were fastened to the implant analogs seated within the master model; a customary polyvinylsiloxane (PVS) impression was registered, and from this a type-IV stone cast was obtained. Scan bodies were then attached to this stone replica and imaged via the Concept Scan Top™ laboratory scanner.

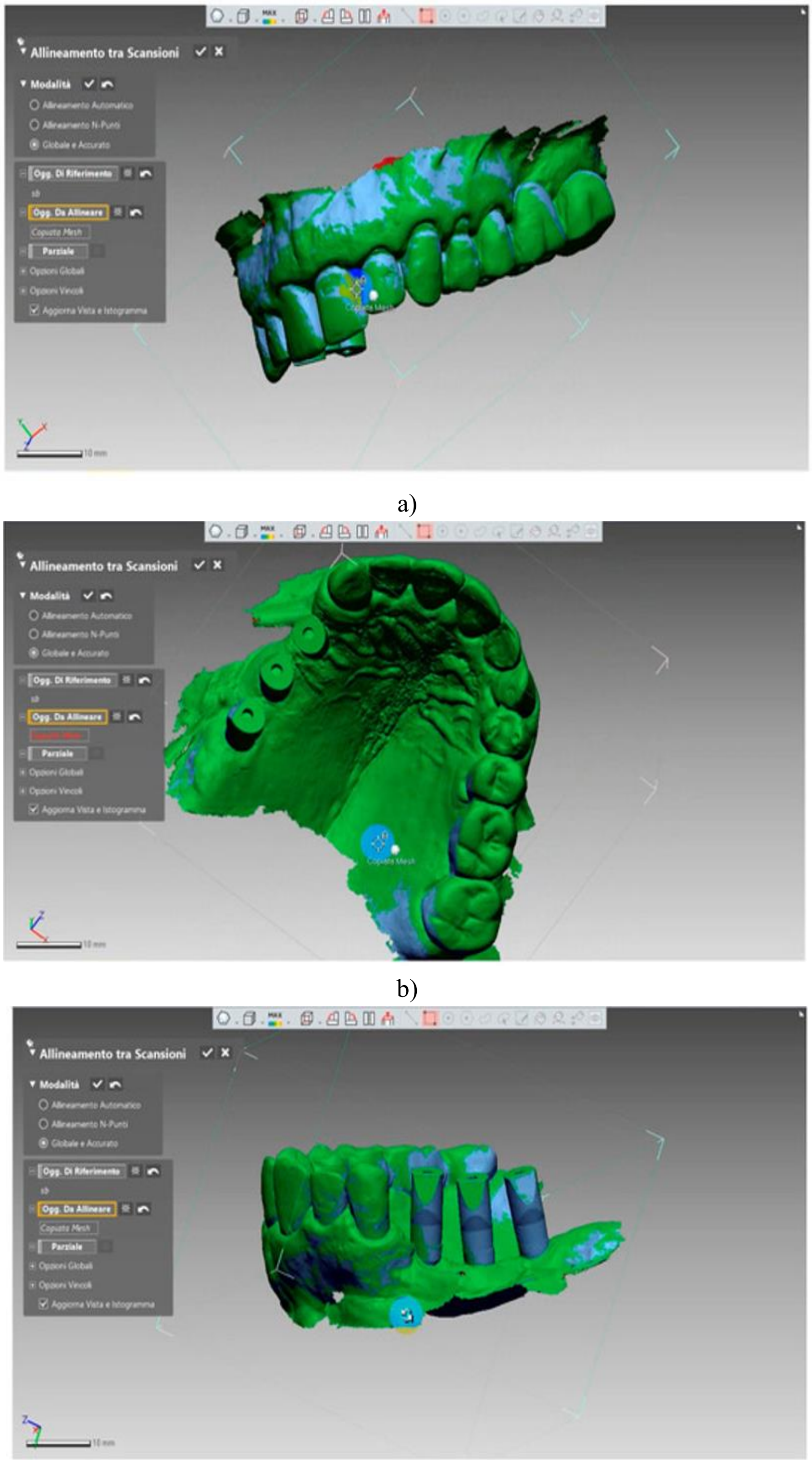
The yardstick for assessing the fidelity of both the post-scan 3D-printed models and the plaster casts derived from conventional impressions was the Concept Scan Top™ laboratory scanner, selected for its extremely low intrinsic deviation. Surface congruence was examined by overlaying the exported STL files within the Gom Inspect software environment (Zeiss®, Oberkochen, Germany). Each test impression was first manually coarse-matched to its laboratory-scanner reference counterpart **(Figures 1a and 1b)**. Following this preparatory orientation, the software's Best-Fit module took over, algorithmically marrying the two surfaces **(Figures 2a–2c)**. The underlying computational logic seeks out and aligns contiguous overlapping patches shared by the two geometries, producing a registration outcome that does not hinge on user skill and yields highly repeatable superimposition. The scanner type being used was not concealed from the operator. Distance computations between superimposed models were generated and are reported in millimeters (mm). For every case, the Gom Inspect package outputted the deviation at each sampled location, the arithmetic mean across the entire surface, and the associated standard deviation.


Allineamento tra Scansioni
Modalità
○ Allineamento Automatico
● Allineamento N-Punti
○ Globale e Accurato
Ogg. Di Riferimento
Ogg. Da Allineare
Copiato Mesh
☑ Allineamento Accurato

a)

b)

Figure 1. (a, b) Landmark points chosen by the operator to seed the initial alignment.



a)

b)

c)

Figure 2. (a–c) Algorithmic Best-Fit refinement is performed by the software based on its internal matching logic.

Statistical analysis

All statistical calculations were executed with AnalystSoft StatPlus® (AnalystSoft Inc., Alexandria, VA, USA, Version 1). GOM Inspect by Zeiss® (Zeiss, Oberkochen, Germany) was used to compute the mean deviation for each model relative to the reference file. These figures were stated in absolute terms. For the three test techniques under investigation (TRIOS®-3Shape, CS 3600® Carestream Dental, and PVS), the average values based on superimpositions of 51 models were determined, yielding the mean deviation for each approach relative to the reference.

For each impression method, the surface discrepancy between the test and reference models was determined using the Best-Fit alignment tool in GOM Inspect (Zeiss®, Oberkochen, Germany). The application measured the linear gap between matching surface points of the two superimposed STL files. The mean deviation per model was taken as the arithmetic mean of all absolute distance values (in µm) at every surface point. In contrast, the standard deviation characterized the variability of these values around the mean. In this way, every master model generated a single mean deviation figure, indicative of its overall trueness compared to the reference scan.

To examine the data, a one-way ANOVA and a two-sample Z-test were conducted, employing a significance threshold (α) of 0.05. Both tests served to contrast the mean distances and to appraise the standard deviations. A technique was deemed accurate provided its mean deviation fell below 30 µm.

Results and Discussion

An overall set of 51 models was examined**. Table 1** details the mean deviation (trueness) and standard deviation (precision) results for every impression technique. The two intraoral scanners—Trios 3Shape® and Carestream CS 3600®—registered lower mean deviation and diminished variability in comparison with the conventional PVS impressions. To be precise, the mean ± SD readings were 13 ± 79 µm for Trios 3Shape®, 12 ± 82 µm for CS 3600®, and 25 ± 213 µm for PVS.

Table 1. Absolute values in millimeters of the mean deviations for each model, corresponding standard deviations, and final average values for the three impression techniques.

No.	Code	PVS SD	PVS mean	Carestream 3600® SD	Carestream 3600® mean	TRIOS 3Shape® SD	TRIOS 3Shape® mean
0	0TAGI	0.16	0.01	0.09	0.02	0.08	0.03
1	1MAFA	0.13	0.04	0.05	0.00	0.06	0.01
2	2DESA	0.14	0.03	0.10	0.03	0.07	0.00
3	3MOSA	0.24	0.05	0.07	0.01	0.06	0.02
4	4ANCA	0.19	0.05	0.09	0.01	0.08	0.02
5	5DEDO	0.35	0.04	0.08	0.02	0.08	0.02
6	6RIMA	0.24	0.03	0.10	0.01	0.09	0.01
7	7CATA	0.20	0.02	0.08	0.00	0.08	0.00
8	8GIPE	0.32	0.00	0.12	0.01	0.08	0.00
9	9NILU	0.18	0.03	0.13	0.01	0.07	0.01
10	10ALSA	0.23	0.01	0.12	0.02	0.12	0.00
11	11NEDA	0.25	0.04	0.05	0.01	0.07	0.01
12	12MEYU	0.24	0.04	0.08	0.01	0.13	0.04
13	13NAGI	0.23	0.01	0.08	0.01	0.08	0.01
14	14SCSA	0.33	0.02	0.07	0.00	0.07	0.00
15	15YUME	0.14	0.01	0.07	0.01	0.11	0.04
16	16CAAN	0.20	0.04	0.08	0.01	0.08	0.01
17	17DISA	0.22	0.02	0.09	0.02	0.07	0.01
18	18PRPA	0.24	0.02	0.07	0.00	0.06	0.01
19	19LOGR	0.18	0.02	0.05	0.00	0.06	0.01
20	20PEGI	0.20	0.03	0.08	0.02	0.05	0.01
21	21BRRO	0.11	0.01	0.07	0.00	0.07	0.01
22	22BUMA	0.13	0.00	0.09	0.02	0.08	0.01
23	23MOIV	0.27	0.00	0.07	0.01	0.07	0.00
24	24POEL	0.28	0.01	0.06	0.00	0.06	0.00
25	25LILU	0.28	0.03	0.08	0.00	0.08	0.02
26	26FEGI	0.25	0.03	0.12	0.02	0.23	0.03
27	27FELA	0.22	0.05	0.07	0.03	0.07	0.02
28	28TAMA	0.33	0.01	0.10	0.01	0.07	0.02
29	29TAPR	0.25	0.01	0.09	0.02	0.09	0.02
30	30MALI	0.15	0.00	0.06	0.01	0.07	0.00
31	31MARI	0.17	0.04	0.08	0.03	0.07	0.00
32	32DARE	0.30	0.03	0.10	0.02	0.11	0.03

33	33DEVI	0.28	0.05	0.08	0.00	0.10	0.01
34	34BRMA	0.25	0.05	0.08	0.01	0.07	0.02
35	35GRLO	0.14	0.02	0.09	0.02	0.10	0.03
36	36TRCO	0.17	0.04	0.06	0.01	0.07	0.01
37	37FRBA	0.22	0.00	0.05	0.01	0.06	0.02
38	38FAGI	0.08	0.02	0.05	0.00	0.05	0.02
39	39VIMA	0.18	0.03	0.08	0.02	0.08	0.00
40	40AVDI	0.19	0.04	0.07	0.02	0.08	0.01
41	41GUFA	0.10	0.00	0.07	0.01	0.07	0.01
42	42DODE	0.19	0.01	0.13	0.00	0.07	0.01
43	43FAGU	0.15	0.00	0.07	0.01	0.08	0.01
44	44SCGE	0.30	0.03	0.09	0.01	0.07	0.01
45	45COMC	0.20	0.04	0.08	0.02	0.07	0.01
46	46FIGI	0.19	0.02	0.06	0.01	0.06	0.01
47	47FAMA	0.26	0.03	0.09	0.01	0.05	0.00
48	48PAPA	0.21	0.04	0.11	0.02	0.08	0.03
49	49ABAL	0.30	0.01	0.07	0.01	0.07	0.01
50	50PIFA	0.12	0.04	0.09	0.00	0.08	0.00

Upon inspection of signed deviations **(Table 2)**, Trios 3Shape® showed a tendency to yield slightly more negative deflections, whereas PVS was characterized by a dominance of positive deflections, pointing to dimensional overestimation. Carestream CS 3600® revealed a well-balanced spread around zero.

Table 2. Displacement values in mm, considering both positive and negative values.

	Code	**PVS SD**	**PVS mean**	**Carestream 3600® SD**	**Carestream 3600® mean**	**TRIOS 3Shape® SD**	**TRIOS 3Shape® mean**
0	0TAGI	0.16	−0.01	0.09	−0.02	0.08	−0.03
1	1MAFA	0.13	0.04	0.05	0.00	0.06	0.01
2	2DESA	0.14	0.03	0.10	0.03	0.07	0.00
3	3MOSA	0.24	0.05	0.07	−0.01	0.06	−0.02
4	4ANCA	0.19	0.05	0.09	−0.01	0.08	−0.02
5	5DEDO	0.35	0.04	0.08	−0.02	0.08	−0.02
6	6RIMA	0.24	−0.03	0.10	−0.01	0.09	−0.01
7	7CATA	0.20	0.02	0.08	0.00	0.08	0.00
8	8GIPE	0.32	0.00	0.12	−0.01	0.08	0.00
9	9NILU	0.18	0.03	0.13	0.01	0.07	0.01
10	10ALSA	0.23	0.01	0.12	0.02	0.12	0.00
11	11NEDA	0.25	0.04	0.05	0.01	0.07	−0.01
12	12MEYU	0.24	0.04	0.08	−0.01	0.13	−0.04
13	13NAGI	0.23	0.01	0.08	0.01	0.08	0.01
14	14SCSA	0.33	0.02	0.07	0.00	0.07	0.00
15	15YUME	0.14	0.01	0.07	0.01	0.11	0.04
16	16CAAN	0.20	0.04	0.08	0.01	0.08	−0.01
17	17DISA	0.22	−0.02	0.09	0.02	0.07	−0.01
18	18PRPA	0.24	0.02	0.07	0.00	0.06	−0.01
19	19LOGR	0.18	0.02	0.05	0.00	0.06	−0.01
20	20PEGI	0.20	0.03	0.08	0.02	0.05	−0.01
21	21BRRO	0.11	0.01	0.07	0.00	0.07	0.01
22	22BUMA	0.13	0.00	0.09	−0.02	0.08	−0.01
23	23MOIV	0.27	0.00	0.07	0.01	0.07	0.00
24	24POEL	0.28	0.01	0.06	0.00	0.06	0.00
25	25LILU	0.28	0.03	0.08	0.00	0.08	−0.02
26	26FEGI	0.25	0.03	0.12	0.02	0.23	0.03
27	27FELA	0.22	0.05	0.07	−0.03	0.07	−0.02
28	28TAMA	0.33	0.01	0.10	−0.01	0.07	−0.02
29	29TAPR	0.25	0.01	0.09	0.02	0.09	−0.02
30	30MALI	0.15	0.00	0.06	−0.01	0.07	0.00

31	31MARI	0.17	0.04	0.08	0.03	0.07	0.00
32	32DARE	0.30	0.03	0.10	0.02	0.11	0.03
33	33DEVI	0.28	0.05	0.08	0.00	0.10	−0.01
34	34BRMA	0.25	0.05	0.08	0.01	0.07	−0.02
35	35GRLO	0.14	0.02	0.09	0.02	0.10	0.03
36	36TRCO	0.17	0.04	0.06	0.01	0.07	0.01
37	37FRBA	0.22	0.00	0.05	−0.01	0.06	−0.02
38	38FAGI	0.08	−0.02	0.05	0.00	0.05	−0.02
39	39VIMA	0.18	−0.03	0.08	−0.02	0.08	0.00
40	40AVDI	0.19	0.04	0.07	0.02	0.08	0.01
41	41GUFA	0.10	0.00	0.07	0.01	0.07	0.01
42	42DODE	0.19	0.01	0.13	0.00	0.07	0.01
43	43FAGU	0.15	0.00	0.07	0.01	0.08	0.01
44	44SCGE	0.30	0.03	0.09	0.01	0.07	−0.01
45	45COMC	0.20	0.04	0.08	0.02	0.07	0.01
46	46FIGI	0.19	0.02	0.06	−0.01	0.06	−0.01
47	47FAMA	0.26	−0.03	0.09	0.01	0.05	0.00
48	48PAPA	0.21	0.04	0.11	−0.02	0.08	−0.03
49	49ABAL	0.30	0.01	0.07	0.01	0.07	−0.01
50	50PIFA	0.12	0.04	0.09	0.00	0.08	0.00

The ANOVA **(Table 3)** revealed statistically significant differences among the three approaches ($P < 0.001$). Pairwise contrasts using the Z-test **(Table 4)** indicated that both digital systems achieved significantly higher accuracy than PVS ($P < 0.001$), whereas no statistically significant difference emerged between the two scanners ($P = 0.60$).

Table 3. ANOVA test between the means of the obtained values.

Source of variation	Omega squared (ω^2)	Fcrit	P-value	F-value	Mean square (MS)	Sum of squares (SS)	Degrees of freedom (d.f.)
Between Groups	0.18296	3.05637	8.8×10^{-8}	18.13015	0.00265	0.0053	2
Within Groups	—	—	—	—	0.00015	0.02191	150
Total	—	—	—	—	—	0.0272	152

Table 4. Z-test between the mean values obtained with the three methods.

Comparison	Critical Z value (Two-tailed)	P-value ($\alpha = 0.05$)	Z value
TRIOS 3Shape® vs Carestream CS 3600®	1.9599	0.6017	0.5218
TRIOS 3Shape® vs PVS	1.9599	0.0000067	4.5018
Carestream CS 3600® vs PVS	1.9599	0.00000023	5.1663

Exhibited a non-normal spread featuring multiple outliers, most notably within the PVS group.

Figure 1 shows the overall distribution of deviations. Every technique stayed within the clinically permissible limit of 30 µm. Nonetheless, the digital systems displayed tighter scatter and greater consistency, as demonstrated by their lower SD values **(Tables 5 and 6)**.

Table 5. ANOVA test for differences in the DVS values obtained with the three methods.

Source of variation	Omega squared (ω^2)	F critical	P-value	F-statistic	Mean square (MS)	Sum of squares (SS)	Degrees of freedom (d.f.)
Between groups	0.68864	3.05637	0	170.19596	0.30097	0.60195	2
Within groups	—	—	—	—	0.00177	0.26526	150
Total	—	—	—	—	—	0.86721	152

Table 6. Z-test between the DVS of values obtained with the three methods.

Comparison	Critical Z value (Two-tailed)	P-value ($\alpha = 0.05$)	Z value
TRIOS 3Shape® vs Carestream CS 3600®	1.9599	0.5897	0.5391

TRIOS 3Shape® vs PVS	1.9599	0.0000	13.7027
Carestream CS 3600® vs PVS	1.9599	0.0000	13.9043

The deviation from the reference value was recorded on average as follows **(Table 1)**:

- (GROUP 1) TRIOS®-3Shape digital impression: mean of 13 µm, with a standard deviation of 79 µm.
- (GROUP 2) CS 3600®–Carestream Dental digital impression: mean of 12 µm, with a standard deviation of 82 µm.
- (GROUP 3) Polyvinyl Siloxane impression: mean of 25 µm, with a standard deviation of 213 µm.

Based on the descriptive statistics, it can be inferred that all three approaches exhibit considerable accuracy, as their deviations from the reference—treated as having negligible error—fall within a few µm of the reference value (below the 30 µm threshold).

Some notable descriptive observations emerge when considering the RELATIVE VALUES, i.e., the signed average displacement magnitudes of the three methods **(Table 2)**. The GOM Inspect software automatically assigned a positive or negative sign based on the direction of the deviation between the test and reference surfaces. Positive magnitudes meant the test surface was positioned outward (above) the reference model, while negative magnitudes indicated the test surface lay inward (below) the reference surface. Such signed deviations offered a qualitative view of error directionality in the color-mapping analysis.

From a qualitative inspection of the techniques **(Figure 1)**, several points can be drawn:

- TRIOS®-3Shape presents a marginally higher frequency of negative deviations.
- PVS demonstrates a marked predominance of positive deviations.
- CS 3600®–Carestream Dental reveals a nearly balanced frequency of positive and negative values.

The IOS systems, TRIOS 3Shape® and Carestream CS3600®, generally yield mean deviation values close to zero. Nevertheless, a shift toward negative values is observable for TRIOS 3Shape®, and toward positive values for Carestream CS3600® [16].

Both the mean and the median suggest that most measurements cluster near zero. It can thus be deduced that the two IOS systems produce statistically similar outcomes relative to the reference point.

By contrast, the analog PVS impression shows deviation values that predominantly lean toward positive values, suggesting that, in the present research, the analog material tends to overstate real dimensions. Further, the span of deviations is broader than with digital systems, and both the mean and median are displaced from zero, indicating that most measurements depart more markedly from the reference value, unlike the pattern observed with the IOS systems.

In brief, IOS systems such as TRIOS 3Shape® and Carestream CS3600® appear to yield more accurate results than the analog PVS material, thereby reducing the likelihood of under- or overestimation in morphological and geometric measurements.

The statistical evaluation was initiated with a one-way ANOVA test **(Table 3)**, examining the mean deviation readings of the three measurement techniques and employing a significance cut-off (α) of 0.05.

The analysis revealed statistically significant differences among the techniques. Because the F-value exceeded the critical F-value, it was inferred that a meaningful statistical difference exists among the three examined methods. Moreover, the p-value proved extremely small, confirming that the detected differences are unlikely to be random. Hence, since the p-value lay below α, the null hypothesis was dismissed.

The evaluation then proceeded with the two-sample Z-test **(Table 4)** to determine which groups showed statistically significant differences.

Insights from the pairwise comparison of mean deviations:

- TRIOS 3Shape® versus Carestream CS3600®: With the Z-value falling under the critical Z, no statistically meaningful distinction in accuracy exists between TRIOS 3Shape® and Carestream CS3600®. A 60% probability additionally indicates that the findings may result from chance. Accordingly, as the p-value exceeds α, the null hypothesis is retained.
- TRIOS 3Shape® versus PVS: As the Z-value stands above the critical Z, a statistically meaningful distinction in accuracy exists between TRIOS 3Shape® and PVS. The likelihood of chance findings here is effectively negligible. Therefore, with the p-value below α, the null hypothesis is dismissed.
- Carestream CS3600® versus PVS: Since the Z-value surpasses the critical Z, a statistically meaningful distinction in accuracy is present between Carestream CS3600® and PVS. Likewise, the role of chance in these outcomes is

nearly zero. Consequently, given the p-value under α, the null hypothesis is dismissed.

It may therefore be concluded that the two digital scanners demonstrate comparable accuracy, despite showing statistically significant differences compared with the analog technique. Accordingly, the null hypothesis is dismissed.

The statistical inquiry next examined the standard deviation (SD) for each measurement **(Tables 1 and 2)**, as provided by the GOM software. This metric captures the spread of the data around a central value, represented here by the mean.

Earlier, the mean standard deviation for every impression technique had been determined **(Table 1)**:

- TRIOS 3Shape®: 79 µm;
- Carestream CS3600®: 82 µm;
- PVS: 213 µm.

Under a significance level of 0.05, an ANOVA test **(Table 5)** was performed to examine whether the standard deviations tied to the mean deviations of the three techniques differed. The outcome indicated significant differences in standard deviation among the three methods investigated.

Because the F-value exceeds the critical F-value, the result indicates that the three analyzed techniques differ significantly. The p-value is also virtually zero, indicating that the results are highly unlikely under chance alone. Hence, with a p-value smaller than α, the null hypothesis is dismissed.

Next, a two-sample Z-test **(Table 6)** was performed to identify which group pairs showed statistically significant differences.

Breakdown of standard deviation comparisons:

- TRIOS 3Shape® versus Carestream CS3600®: The Z-value falls below the critical Z, meaning the standard deviations of TRIOS 3Shape® and Carestream CS3600® do not differ in a statistically meaningful way. There is a 58% chance that the observed effect is due to random variatijon. Accordingly, as the p-value exceeds α, the null hypothesis is retained.
- TRIOS 3Shape® versus PVS: Here, the Z-value lies above the critical Z, so the standard deviations of TRIOS 3Shape® and PVS are significantly different from a statistical standpoint. The chance that randomness accounts for the results is negligible, leading to the rejection of the null hypothesis.
- Carestream CS3600® versus PVS: The Z-value again tops the critical Z, establishing a statistically significant difference between the standard deviations of Carestream CS3600® and PVS. The p-value is minimal, and thus the null hypothesis is rejected.

The Z-test analysis reveals that the two IOS platforms cover roughly equivalent standard deviation ranges, reflecting similar consistency. Crucially, though, both digital modalities differ significantly from the analog workflow, indicating that PVS impressions exhibit larger standard deviations.

Rephrased, the intraoral scanner data display tighter consistency with reduced spread relative to the conventional approach. This implies that the analog method introduces greater deviations, potentially compromising measurement precision and the reliability of outcomes.

The graphical display above reinforces this point:

Analog impression standard deviations are uniformly larger than those gathered from the IOS units, and the fluctuation among separate standard deviation readings is also markedly more pronounced. This plainly signals broader data scatter within the analog impressions.

Ultimately, the conventional technique yields greater variability in the recorded data, accompanied by meaningful discrepancies between individual measurements.

The present work demonstrates that while each of the three impression modalities assessed—TRIOS® 3Shape and Carestream CS 3600® intraoral scanners, along with polyvinyl siloxane conventional impressions—delivered high accuracy with mean deviations staying below 30 µm, digital impressions nonetheless offered substantially better precision than their traditional counterpart. Therefore, the initial null hypothesis that there was no meaningful accuracy gap between digital and conventional approaches was overturned. No statistically significant difference, however, emerged between the two scanner types. These observations reinforce the view that digital tools mark progress over analog workflows, even though every system evaluated stays within clinically admissible bounds.

The TRIOS® 3Shape intraoral scanner is built around focal microscopy, harnessing an LED illuminator and a rasterized laser pattern to reconstruct three-dimensional surfaces from variations in reflected light and focal sharpness. Its Ultrafast Optical Scanning, supplemented by Real Color technology, collects several thousand 3D frames, which are fused into a lifelike digital model stored in STL format for straightforward lab transfer. The unit incorporates a smart touch panel, anti-fog tips compatible with autoclaving, and swappable scan heads suited to both arches. The manufacturer states accuracy of 6.9 ± 0.9 µm and precision of 4.5 ± 0.9 µm [17, 18].

The Carestream Dental CS 3600® device uses structured LED illumination to capture full-color three-dimensional surfaces and save them as STL files, enabling smooth integration with open-architecture software. Continuous scanning functionality permits uninterrupted capture even when unexpected motion occurs, improving procedural steadiness. Audio cues, live directional arrow overlays, and tinted alerts for missing or faulty scan regions are built in. An integrated heating element combats fog formation, and the autoclavable, exchangeable tips support flexible scanning workflows [19, 20].

Polyvinyl siloxane, an elastomer, was selected on account of its excellent precision, high accuracy, favorable rigidity, and outstanding elastic rebound. It strongly resists distortion and guarantees sustained dimensional integrity. Impressions were made via a single-step technique, and casts were subsequently fabricated from low-expansion Type IV dental stone [20].

The Concept Scan Top™ laboratory scanner operates through blue structured light acquisition and a five-axis motion platform. Digitizing a complete arch takes roughly 40-60 s and produces files in STL, OBJ, OFF, and PLY container formats. Its stated performance parameters are 5 µm accuracy, 2 µm precision, and 5 µm resolution.

During the digital capture phase, after the 51 models were scanned with the two intraoral devices, the resulting virtual volumes were exported in STL format to enable superimposition and comparative analysis. Faithfully recording an impression to generate a model that closely mirrors clinical reality is an essential prerequisite for crafting precise dental restorations. This step requires careful handling, as multi-stage traditional workflows frequently compound errors. Modern CAD-CAM digital pathways aim to streamline these stages and mitigate some shortcomings of physical impressions. Studies comparing intraoral scanners with conventional methods are increasingly documenting encouraging outcomes.

A substantial body of literature has examined how digital intraoral scanners compare with conventional impression techniques. Still, results often diverge due to the lack of a universally agreed-upon benchmark for comparison. The threshold for clinically acceptable misfit is still under discussion; some authors advocate a limit of up to 30 µm [20], while others consider up to 150 µm acceptable [21]. For this study, the 30 µm value is taken as the standard for defining an accurate impression system.

In a systematic review, Rutkūnas *et al.* [22] concluded that newer-generation IOS devices deliver accuracy equivalent to or better than that of traditional methods. However, the review's scope was limited to a single in vivo investigation among 16 studies. Research published by Roig *et al.* [13] indicated that the CEREC® Omnicam IOS was less accurate than polyether impressions, whereas competing digital systems were more accurate than conventional techniques. Similarly, a study by Albayrak *et al.* [23] showed that IOS platforms achieved greater accuracy than traditional approaches, particularly in full-arch implant contexts [13].

Nevertheless, some authors, for instance, Nedelcu *et a*l. [24], maintain that conventional methods, including polyether impressions, may outperform digital systems in terms of accuracy, especially in non-implant cases. Investigations comparing accuracy across different iOS brands have reported heterogeneous results, largely due to differences in scanning workflows, software, and hardware specifications. In sum, while intraoral scanners show encouraging accuracy levels, their actual performance depends on multiple factors, including the core scanner technology, whether powder is applied, and the chosen scanning path [24].

The scan fidelity attainable with the TRIOS® 3Shape unit is further substantiated by a 2020 systematic review from Kihara *et al.* [25], which found that the TRIOS® 3Shape scanner yielded the highest-quality results among the reviewed papers, singling it out as the IOS system that most closely approximates the performance of laboratory-grade scanners.

The data gathered in the current work led to rejection of the null hypothesis, which assumed that IOS and analog impressions would exhibit similar accuracy in implant rehabilitation. In practice, both mean accuracy and measurement scatter were inferior for PVS compared with the digital techniques. Still, all three approaches fell within the clinically allowable band of 30 µm. Studies that favor IOS technology often attribute this advantage to the chain of steps embedded within traditional workflows, each of which can introduce additive errors that compromise overall precision (e.g., faults in the analog impression itself, gypsum model expansion, and scanning inaccuracies in the laboratory unit).

Points of divergence from earlier publications can be traced to differences in how accuracy was assessed and which software was applied for digital alignment. To illustrate, references [16, 24] reported superior accuracy for conventional impressions compared with certain IOS devices, particularly in full-arch or extended-span scenarios where stitching artifacts may accumulate. In contrast, reference [16] documented that the Trios® and CS 3600® scanners matched or exceeded the accuracy of analog workflows when restricted to short-span implant cases. Such disparities may arise from variability in the number of implants digitized, the alignment logic selected (Best-Fit vs. feature-based registration), and the surface texture of the master models.

Because the present study focused on partially edentulous casts and used a uniform Best-Fit alignment protocol, the outcomes more closely aligned with those reported by Imburgia *et al*. [12], Kihara *et al*. [25], and diverged from the findings of Roig *et al*. [13] and Nedelcu *et al*. [24], whose experimental designs incorporated full-arch or in vivo conditions where error propagation tends to be greater.

It is likewise important to recognize that operator proficiency and experience are key determinants of measurement accuracy, as a distinct learning curve must be overcome before the clinician can fully capitalize on an IOS device's capabilities. Furthermore, the in vitro nature of this study must be kept in mind, as its findings may not transfer directly to the realities of patient care. During optical scanning, moisture from saliva and blood, along with soft tissue displacement, can substantially interfere with image capture and final impression accuracy. Likewise, moisture may degrade the precision of elastomeric materials. Even so, the present work provides new quantitative support that, under standardized conditions, both the Trios3Shape® and the Carestream CS 3600™ maintain accuracy figures comfortably within the 30 μm clinical boundary, thereby reinforcing their suitability for implant-supported prostheses. A direct head-to-head dataset comparing these two scanners under matched conditions has not appeared in the literature before.

It is also notable that the casts used here were produced via 3D printing and possessed a rougher, drier surface than that encountered inside the mouth. This surface texture may have caused distortions in the traditional materials and hindered their flow during impression-taking. Moreover, the printed models were opaque and free of the reflections typically created by saliva on dental hard tissues and mucosa—conditions that might have facilitated more faithful registration by the IOS devices.

Although the Best-Fit superimposition step is algorithm-driven, our pipeline included a manual pre-alignment phase, and the evaluator was aware of which impression technique had been used. These factors could introduce bias and should be considered a limitation of the present work.

Several limitations of the current investigation deserve mention. First, it was executed in vitro under laboratory-controlled conditions that cannot fully emulate the clinical environment; variables such as salivary flow, soft-tissue mobility, and patient movement may influence in vivo impression accuracy. Second, the absence of operator blinding to the impression modality could have introduced measurement bias during both acquisition and post-processing stages. Third, the study included only partially edentulous models featuring short implant spans, meaning the conclusions cannot be readily extended to full-arch rehabilitations. Moreover, only two intraoral scanners were examined, and both the scanning methodology and the alignment technique (Best-Fit algorithm) could affect the deviation values. Lastly, the evaluation of trueness and precision was based exclusively on surface superimposition, without any assessment of the clinical fit of the prosthetic restorations fabricated from the impressions.

The scope of this investigation was purposely limited to partially edentulous implant cases, reflecting the most commonly encountered clinical situations and lending themselves to reproducible short-span scanning routines. Completely edentulous arches were intentionally omitted, as they pose a different set of technical obstacles—namely, lengthier scan trajectories and a scarcity of anatomical landmarks—that tend to magnify cumulative stitching inaccuracies and compromise overall precision.

The body of published work indicates that, even with steady technological advances, scanning fully edentulous arches with intraoral devices still yields unpredictable findings compared with traditional impressions, most notably in full-arch implant rehabilitations. Accordingly, the present outcomes should be viewed solely through the lens of partially edentulous casts, with no direct extrapolation made to full-arch scenarios.

Acknowledging the inherent restrictions of this in vitro design, corroborative in vivo research is called for to substantiate these results within a clinical setting. Future investigations should compare various intraoral scanning platforms, address full-arch cases, and employ consistent scanning protocols to more thoroughly evaluate the repeatability and practical value of digital versus analog impressions for implant-supported rehabilitation.

It is also worth underscoring that IOS hardware and software are subject to ongoing iterative upgrades, whereas the evolution of polyvinyl siloxane materials has largely reached a mature plateau. As a result, forthcoming head-to-head studies can be expected to tilt ever more decisively toward digital systems as technological refinement persists.

Conclusion

Operating within the acknowledged constraints of this laboratory-based study, all three impression approaches—TRIOS® 3Shape, CS 3600® Carestream Dental, and PVS analog impressions—registered high baseline accuracy, with average deviations remaining below the 30 µm mark relative to the reference model. Both scanner-based systems outperformed the traditional PVS workflow in accuracy and consistency. These data suggest that intraoral scanning can yield more trustworthy, repeatable impressions while mitigating the errors inherent in conventional, multi-step procedures.

The conclusions are strictly grounded in in vitro observations, yet reasonable clinical deductions can still be drawn from them. Seen through a clinical lens, the superior trueness and precision of digital impressions have the potential to enhance passive adaptation of implant-supported restorations, streamline communication with the laboratory, and elevate patient comfort during impression-taking.

Ultimately, supplementary in vivo studies are required to confirm these benefits under everyday clinical conditions and to assess their long-term influence on both prosthetic longevity and implant survival.

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