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To Assess the Effect of Material Type, Implant System- Specific Scan Body and Third-party Scan Body on the Accuracy of Digital Implant Impressions Following Sterilization and Reuse – In Vitro Study

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Abstract

Background: Digital implant impressions rely on scan bodies that require sterilization between clinical uses. The combined effects of scan body material composition, manufacturer origin, and repeated sterilization cycles on impression accuracy remain inadequately characterized.

Objective: To evaluate the influence of scan body material (titanium vs. PEEK), manufacturer origin (original equipment manufacturer [OEM] vs. third-party), and repeated sterilization-reuse cycles (0, 1, 5, and 10 cycles) on the accuracy of digital implant impressions.

Methods: Four scan body groups were evaluated: OEM titanium, OEM PEEK, third-party titanium, and third-party PEEK. A standardized master model with two Dentium Superline implants was used. Each group underwent baseline scanning and repeated cycles of autoclave sterilization (134°C, 2.1 bar, 5 minutes), connection at 10 Ncm torque, intraoral scanning with Primescan intraoral scanner, and disconnection. Ten scans per group-condition combination yielded 160 total scans. Accuracy was assessed using Cloud Compare software through three-dimensional superimposition, measuring root mean square (RMS) error, Euclidean distance deviation, and angular deviation. Statistical analysis employed one-way ANOVA and paired t-tests ($\alpha = 0.05$).

Results: Scan body material, manufacturer origin, and sterilization cycles significantly affected impression accuracy ($p < 0.05$). PEEK scan bodies demonstrated superior dimensional stability across sterilization cycles, with RMS error ranging from 0.150 ± 0.045 mm (cycles 3-4) to 0.273 ± 0.139 mm (cycles 9-10). Titanium scan bodies exhibited greater variability, with RMS error increasing from 0.166 ±

0.059 mm (cycles 1-2) to 0.381 ± 0.210 mm (cycles 9-10). OEM scan bodies generally showed lower RMS error in advanced reuse cycles compared to third-party alternatives, though well-manufactured third-party PEEK scan bodies demonstrated comparable performance. All groups maintained deviations within clinically acceptable limits (<50 µm) after ten sterilization cycles. Angular deviations increased more substantially than linear deviations in later cycles, particularly for titanium scan bodies (0.668 ± 0.388° at cycles 9-10).

Conclusions: Material composition exerted a stronger influence on accuracy than manufacturer origin. PEEK scan bodies demonstrated greater consistency and dimensional fidelity following repeated sterilization. Controlled reuse of scan bodies up to ten cycles is clinically acceptable when proper protocols are implemented. Well-manufactured third-party PEEK scan bodies may offer cost-effective alternatives to OEM components without compromising accuracy.

Keywords: Digital Impression; Scan Body; Sterilization; PEEK; Titanium; Implant Dentistry; Accuracy; Trueness; Precision

1. Introduction

The incorporation of digital technologies has revolutionized contemporary implant prosthodontics by improving the accuracy, efficiency, and predictability of restorative procedures. Digital workflows have increasingly replaced conventional impression techniques due to their advantages in patient comfort, reduced chairside time, streamlined laboratory procedures, and enhanced communication between clinicians and dental laboratories. The integration of intraoral scanners (IOS) with computer-aided design and computer-aided manufacturing (CAD/CAM) systems has facilitated the development of fully digital implant rehabilitation protocols with clinically acceptable accuracy and reproducibility.[4–9,12–14]

Accurate transfer of the three-dimensional position of dental implants from the oral environment to the virtual workspace remains one of the most critical factors determining the success of implant-supported prostheses. Inaccuracies in implant position transfer can lead to prosthetic misfit, screw loosening, component fracture, unfavorable stress distribution, and biological complications affecting peri-implant tissues. Therefore, obtaining an accurate digital implant impression is essential for achieving long-term prosthetic success.[1,2,13,21,26]

Within digital implant workflows, implant scan bodies serve as intermediary reference components that enable intraoral scanners to capture the exact spatial position, depth, and angulation of dental implants. The scanned geometry is subsequently matched with the corresponding CAD library file to reconstruct the implant position within the virtual environment. Consequently, the dimensional accuracy, manufacturing precision, and positional stability of scan bodies play a fundamental role in determining the overall accuracy of digital implant impressions.[3,20,25,31,38,43]

Numerous factors have been reported to influence the accuracy of digital implant impressions, including scanner technology, scanning strategy, implant angulation, inter-implant distance, operator experience, environmental conditions, and scan body characteristics. Among these variables, scan body material composition and geometric design have gained particular attention because they directly influence optical scanning behavior and positional accuracy.[10,15,19,23,34,36,38,47]

Currently, implant scan bodies are primarily manufactured from titanium and polyetheretherketone (PEEK). Titanium scan bodies possess excellent mechanical strength, rigidity, dimensional stability, and wear resistance. However, their reflective surfaces may interfere with optical scanning technologies under

certain conditions. Conversely, PEEK scan bodies exhibit favorable optical properties due to their low reflectivity, excellent chemical resistance, and adequate dimensional stability, potentially improving scanning performance. Nevertheless, concerns remain regarding the dimensional stability and wear resistance of polymer-based scan bodies following repeated clinical use and sterilization procedures.27,30,33,39,44,48,50,51

Another important consideration is the manufacturer origin of scan bodies. Original equipment manufacturer (OEM) scan bodies are specifically designed for individual implant systems and are generally produced with strict manufacturing tolerances and validated connection geometries. In contrast, third-party scan bodies offer advantages such as lower cost, increased availability, and broader implant compatibility. However, variations in manufacturing tolerances, connection geometry, and material composition may influence their positional accuracy and clinical performance. Recent investigations have demonstrated that while certain third-party scan bodies exhibit performance comparable to OEM components, others demonstrate greater dimensional deviations and reduced reproducibility.[31,32,43,50]

Sterilization protocols represent another clinically relevant factor affecting scan body accuracy. Reusable scan bodies are routinely subjected to repeated autoclave sterilization cycles, exposing them to thermal and mechanical stresses that may alter their dimensional stability, surface characteristics, and seating accuracy. Furthermore, repeated connection and disconnection procedures may accelerate mechanical wear and contribute to cumulative positional errors. Recent studies have demonstrated that repeated sterilization cycles may influence scan body accuracy, although the extent of these changes appears to depend on the scan body material, manufacturing quality, and number of sterilization cycles.39,41,42,52

Although numerous studies have evaluated the influence of scan body material, scanner technology, implant angulation, and scan body geometry individually, limited evidence exists regarding the combined effect of scan body material, manufacturer origin, and repeated sterilization-reuse cycles on digital implant impression accuracy. Furthermore, comparative evidence evaluating system-specific and third-party scan bodies after repeated sterilization remains limited and inconclusive.[31,39,41,42,50,52]

Therefore, the purpose of the present in vitro study was to evaluate the effect of scan body material (titanium versus PEEK), manufacturer origin (system-specific versus third-party), and repeated sterilization-reuse cycles on the accuracy of digital implant impressions. The null hypothesis was that neither scan body material, manufacturer origin, nor repeated sterilization-reuse cycles would significantly affect the accuracy of digital implant impressions.

2. Materials and Methods

2.1 Study Design

This controlled in vitro experimental study employed a four-group design with repeated measures. Each group was subjected to four treatment conditions representing progressive sterilization–reuse cycles (0, 1, 5, and 10 cycles. All scan bodies were standardized in geometry (where possible) to isolate material and manufacturing effects. Each scan body was uniquely coded for tracking throughout the study, and a total of 10 samples per group were included.

Independent variables:

Scan body type (4 groups: A, B, C, D)

Treatment condition (4 levels: 0, 1, 5, and 10 sterilization–reuse cycles)

Dependent variables:

Trueness (Euclidean deviation, RMS error, angular deviation)

Precision (within-group variability)

A total of **160 scans** (4 groups × 4 conditions × 10 repetitions) were obtained, resulting in **320 implant-level measurements**. All equipment was calibrated and used according to manufacturer recommendations to ensure measurement reliability.

2.2 Scan Body Groups

Four scan body groups were evaluated, incorporating two material types (titanium and PEEK) and two manufacturing categories (OEM and third-party):

Group A: System-specific titanium scan bodies (OEM, Dentium Superline)

Group B: System-specific PEEK scan bodies (OEM, Dentium Superline)

Group C: Third-party compatible titanium scan bodies (NMD Medodent)

Group D: Third-party compatible PEEK scan bodies (Shenzhen Sijiemai Technology)

All scan bodies were compatible with Dentium Superline implants featuring internal hexagonal connections.

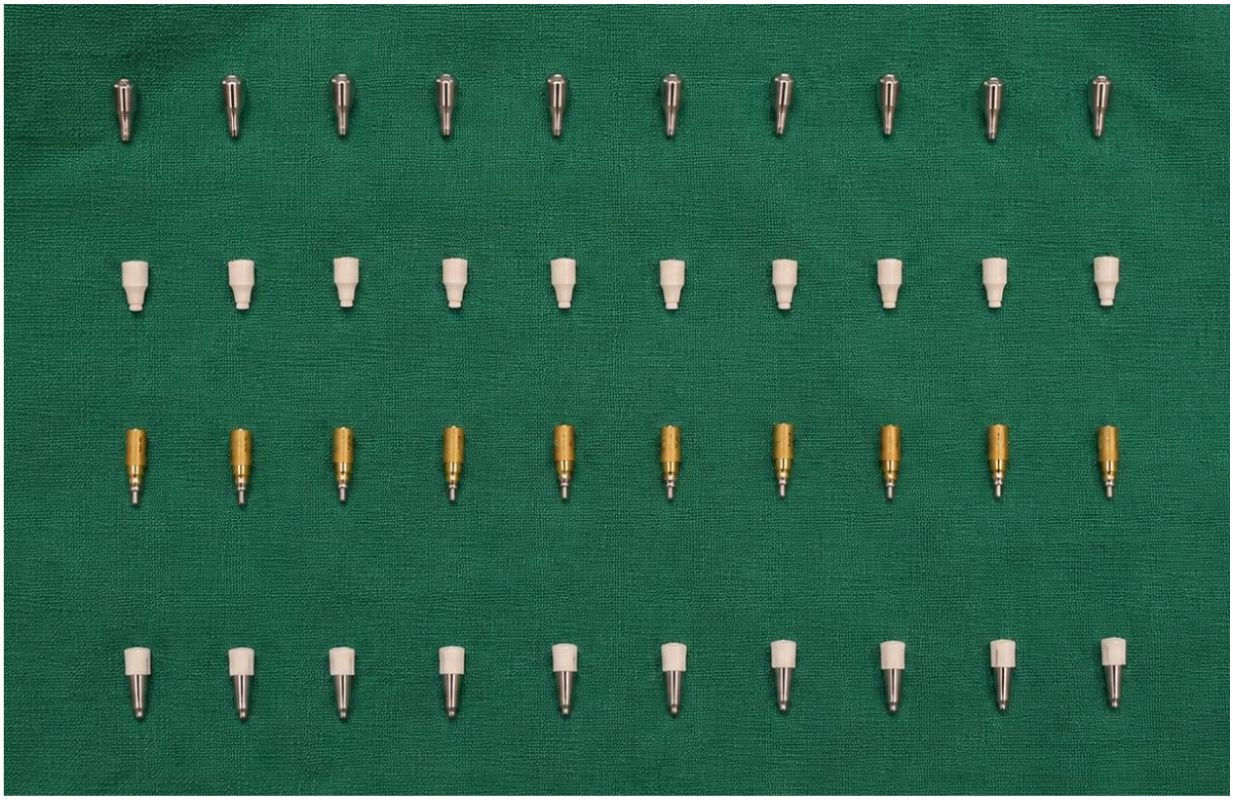

Figure 1: Row 1: Dentium titanium scan bodies, Row 2: Dentium PEEK scan bodies, Row 3: Third-party Compatible Titanium scan bodies, Row 4: Third-party Compatible PEEK scan bodies

2.3 Master Model Preparation

A Prefabricated mandibular master model (resin polymer to mimic bone) was developed to simulate a partially edentulous clinical scenario requiring implant supported prosthetic rehabilitation. The model represented the right posterior mandibular quadrant, incorporating edentulous sites at the second premolar (#45) and first molar (#46) regions, while preserving simulated natural dentition from #42 to #44 region to provide anatomical reference and stability during scanning procedures. Two implants from the Dentium

Superline system (Dentium Co., Ltd., Seoul, South Korea) were placed under standardized conditions. Each implant featured an internal hexagonal connection (2.42 mm diameter, 0.7 mm depth), ensuring stable and precise engagement with prosthetic components. Both implants were identical in dimension (4.0 mm diameter × 10 mm length) to maintain consistency across all experimental procedures. The implants were positioned at the #45 and #46 sites with a centre-to-centre inter-implant distance of approximately 15–18 mm, reflecting a clinically relevant restorative span. Implant placement was carefully standardized: both fixtures were aligned parallel to each other and perpendicular to the occlusal plane (0° divergence) to eliminate angulation-related variables and ensure reproducibility. The implant platforms were positioned 2 mm sub gingivally to simulate clinical placement depth, and were cantered buccolingually within the alveolar ridge to approximate natural bone anatomy and support conditions. The model surface was treated with a light matte spray to minimize reflectivity and optimize scanning conditions.

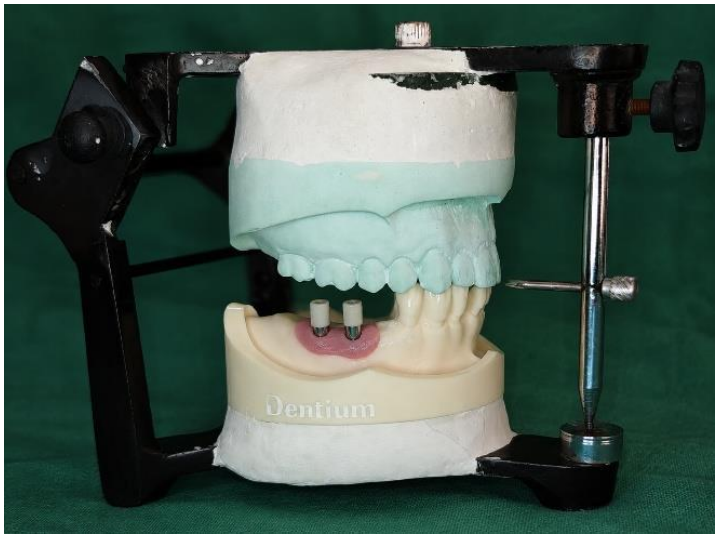

Figure 2: Master model fabrication

A high-resolution dental laboratory scanner (Medit T310 3D) with accuracy ≤5 µm was used to generate a reference STL dataset. This reference scan served as the gold standard for all subsequent accuracy comparisons.

Figure 3: Desktop Lab scanner (Medit T310 3D Dental lab Scanner): High-precision desktop scanner

2.4 Sterilization-Reuse Protocol

Each scan body group was subjected to four treatment conditions representing progressive reuse:
C0 (Baseline): 0 sterilization cycles—new, unused scan bodies
C1: 1 sterilization-reuse cycle
C5: 5 sterilization-reuse cycles
C10:10 sterilization-reuse cycles
Each cycle consisted of the following standardized sequence:

1. Autoclave steam sterilization (134°C, 2.1 bar pressure, 5 minutes exposure time)
2. Cooling period (30 minutes at room temperature)
3. Connection to implant fixture using calibrated torque wrench (10 Ncm)
4. Intraoral scanning
5. Disconnection from implant fixture
6. Cleaning with 70% isopropanol
7. Air drying

This protocol simulated realistic clinical reuse conditions while maintaining standardization across all groups.

2.5 Digital Impression Acquisition

All digital impressions were acquired using a Primescan intraoral scanner (Dentsply Sirona) under standardized environmental conditions (temperature 22 ± 2°C, relative humidity 45-55%). A single experienced operator performed all scans following a consistent scanning protocol to minimize operator-dependent variability.

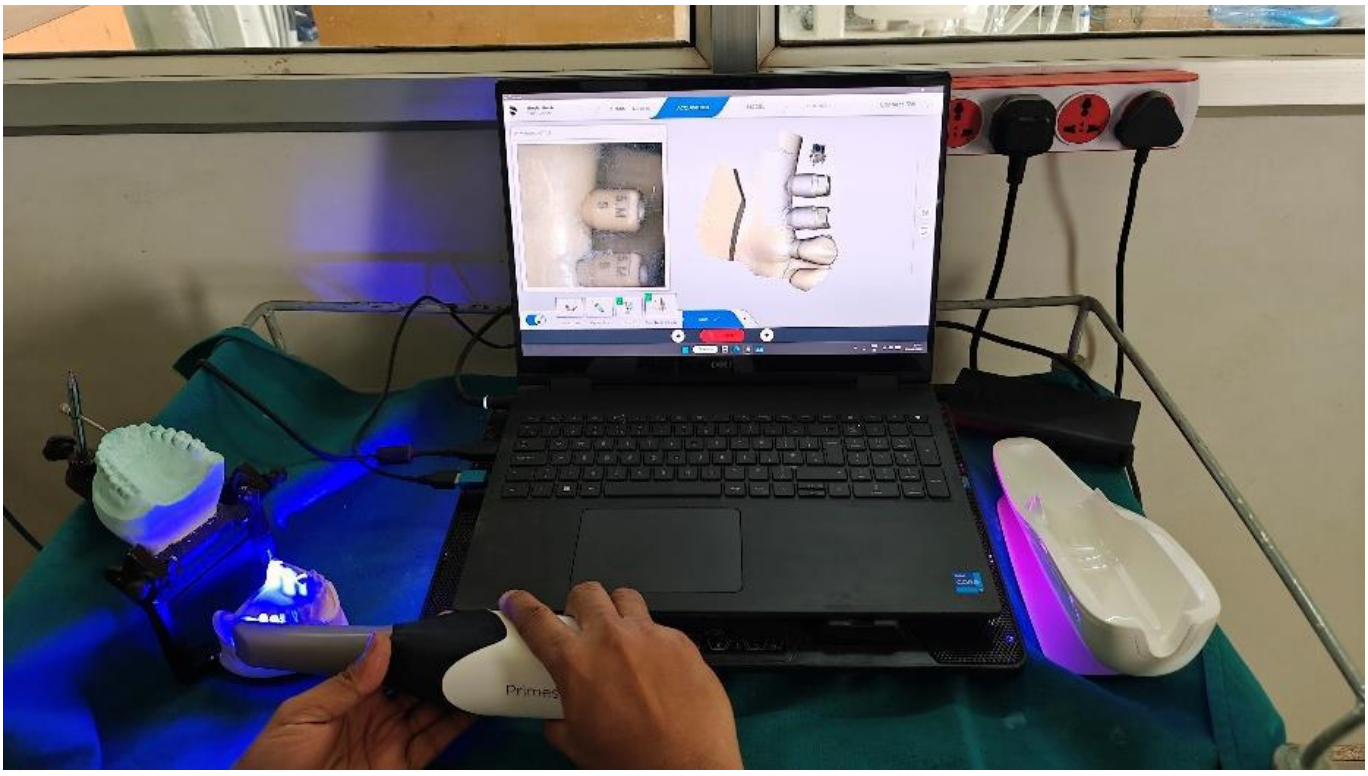

Figure 4: Intraoral scanner Model: Primescan (Dentsply Sirona, Charlotte,NC, USA) and High-performance computer Workstation (Intel Core i9) used under standardised environmental condition processor, 32 GB RAM, NVIDIA RTX graphics)

For each group-condition combination, ten replicate scans were performed, with scan bodies completely removed and reconnected between each scan to simulate clinical variability. This yielded 160 total scans (4 groups × 4 conditions × 10 replicates).

2.6 STL Superimposition and Accuracy Analysis (CloudCompare software Workflow)

Step 1: Data Import and Preparation

- Reference STL file of mandibular ridge (ROI) (Figure 5) and STL file of scan body (figure 6) are imported into Cloud Compare software.

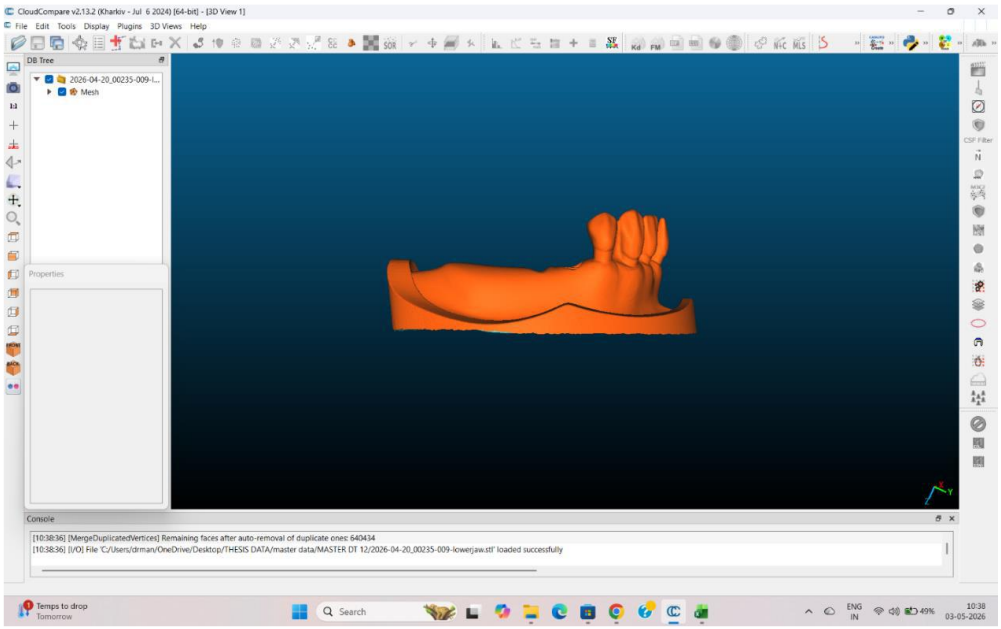

Figure 5: Reference STL file of master model

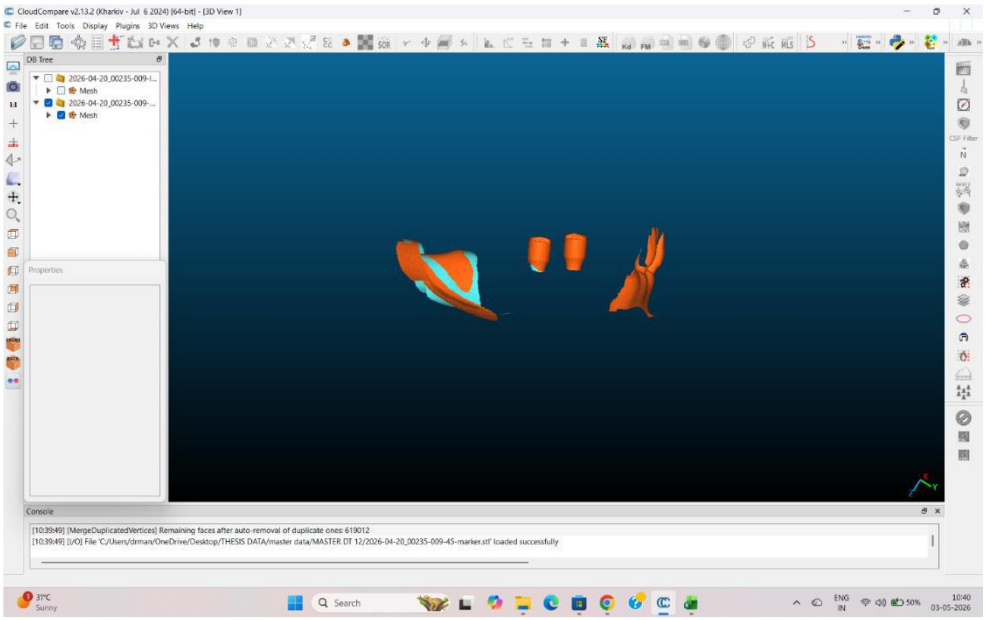

Figure 6: Reference STL file of only Scan body

- Both STL files are Merged together using cloud compare to create Refrence mesh. (Figure 7). Mesh integrity (holes, artifacts, triangle quality) was verified

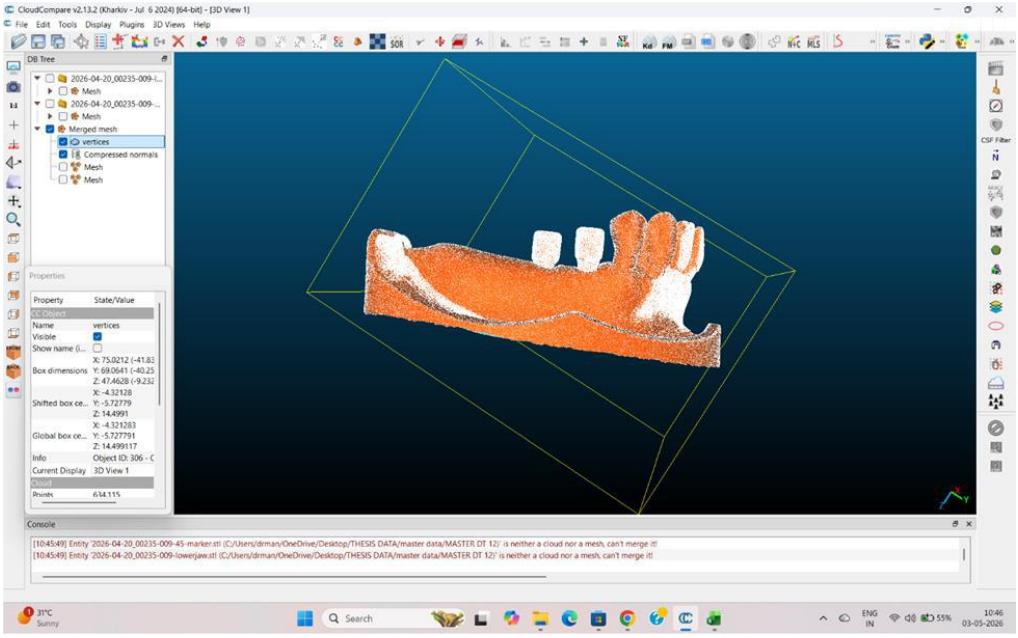

Figure 7: Merged Reference mesh

Step 2: Import of Test STL file labelled according to four groups and sterilisation and reuse cycle. Test STL files is given different colour using colour tool from the software. (Figure 8)

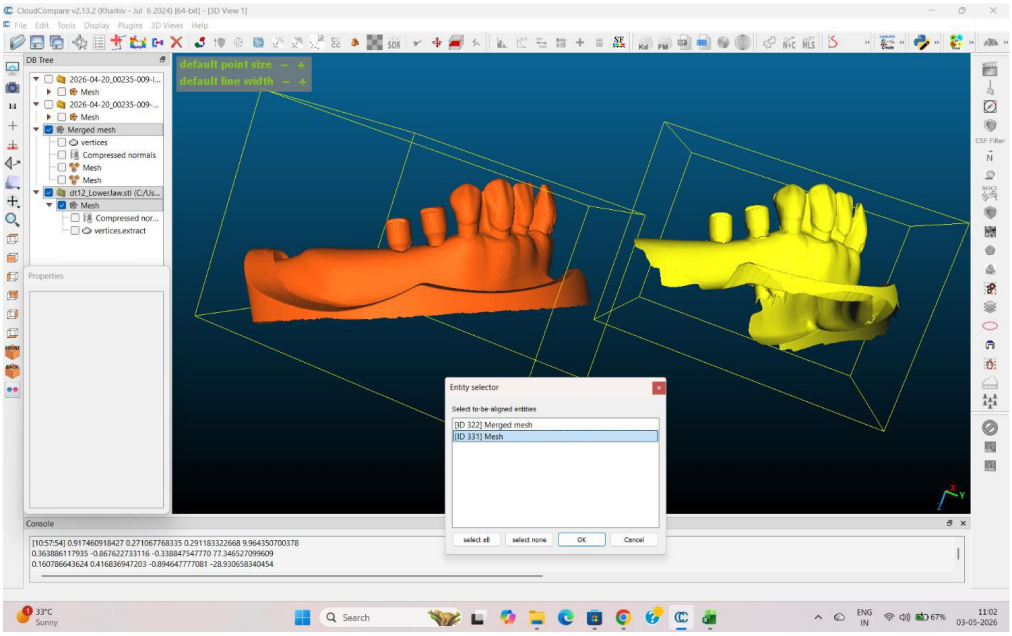

Figure 8: Import of Test STL file and its selection for alignment with Merged Master mesh

Step 3: Alignment

Alignment was performed using **point-pair picking**. Four reference points were selected on the two scan body particularly on the bevel and margins of flat surface in both Master mesh and to be aligned mesh. This ensured consistent and reproducible alignment across all data sets. The software provides three dimensional coordinates of the four reference points selected on the scan body of both Master mesh and Test Mesh (figure 9)

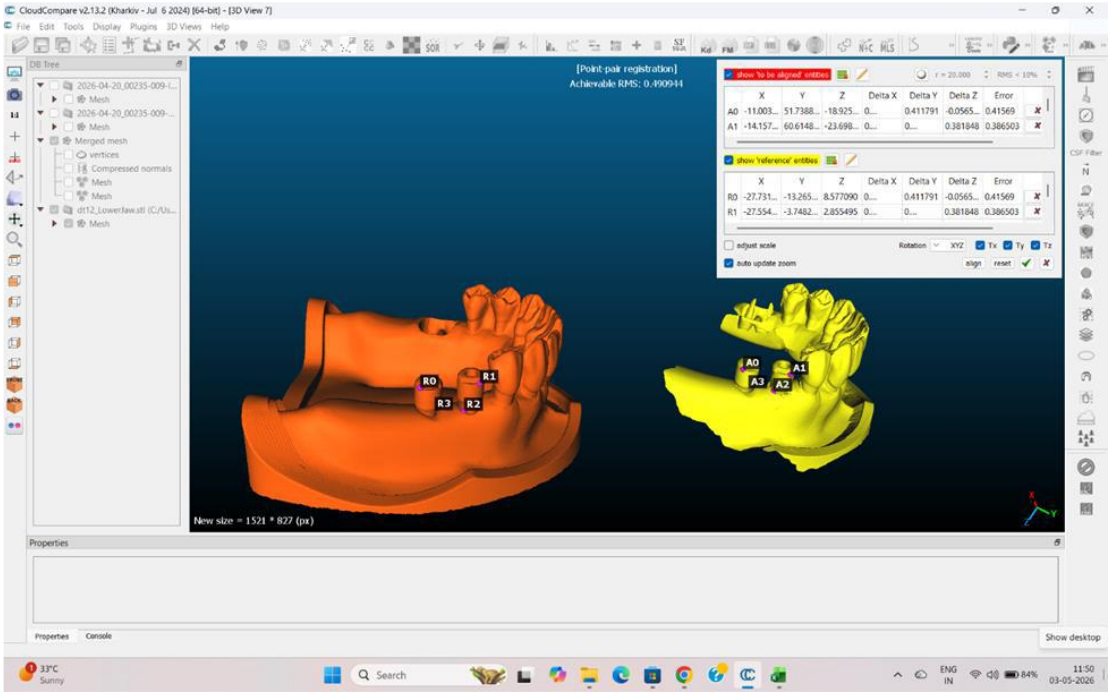

Figure 9: Alignment was performed using four reference points selected on the scan body of both Master mesh and Test Mesh

Step 4: Superimposition of Master mesh and Test mesh (Figure 10)

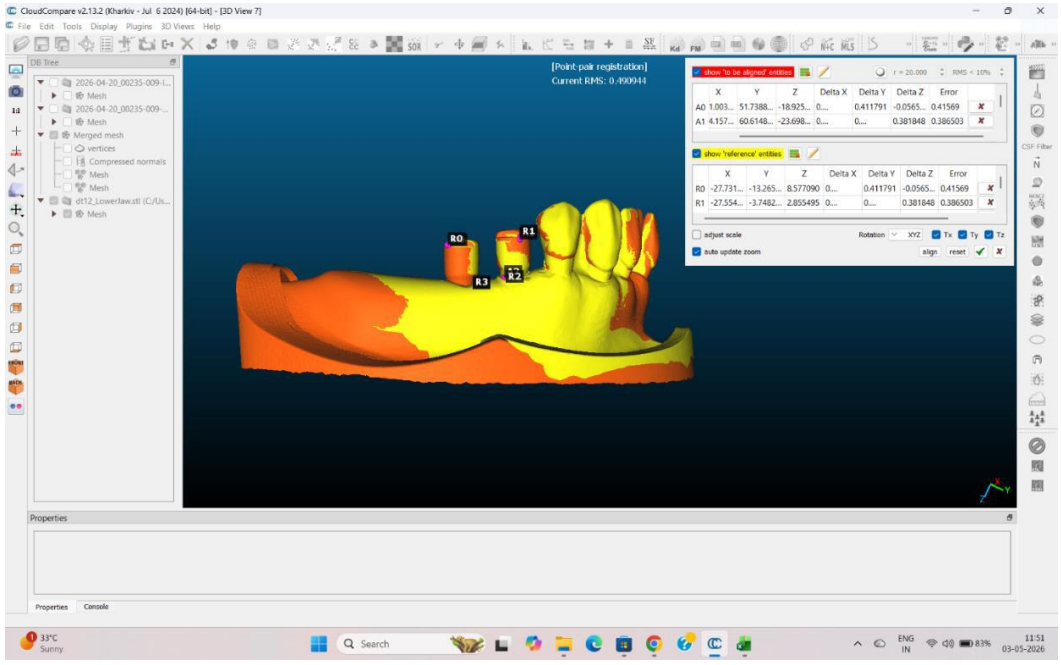

Figure 10: Superimposed mesh

Step 5: Deviation Measurement

Following alignment, cloud-to-mesh distance analysis was performed:

- Reference = master STL
- Compared = test STL

Cloudcompare software provide linear deviation in X,Y,Z coordinates along with RMS error in the console window of software. (Figure 11)

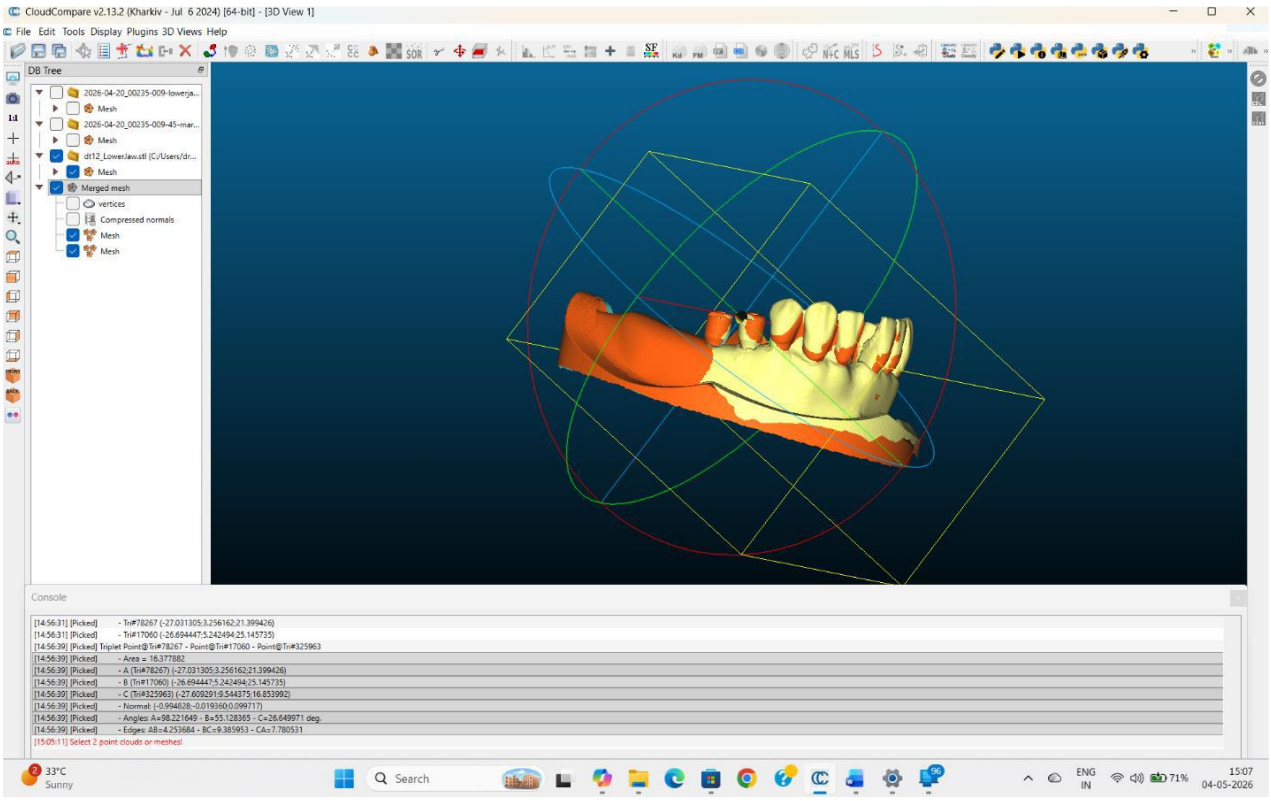

Figure 11 : Linear deviation and RMS error in the console window of software

Step 6: Data Extraction

All numerical data were exported as CSV files for statistical analysis. Each dataset was categorized based on:

- Group
- Cycle condition
- Repetition

2.6 Accuracy Assessment

Three-dimensional accuracy analysis was performed using CloudCompare software (version 2.13.2,Kharkiv – July 2024,). Each test scan was superimposed onto the reference scan using an iterative closest point (ICP) algorithm with fine registration parameters.

Accuracy was quantified using three metrics:

1. **Root Mean Square (RMS) Error:** Overall three-dimensional deviation between test and reference scans, calculated as the square root of the mean squared distances between corresponding points.

2. **Euclidean Distance Deviation:** Linear spatial displacement between corresponding landmarks on test and reference scans, calculated as the straight-line distance in three-dimensional space.
3. **Angular Deviation:** Rotational discrepancy between test and reference scan body orientations, measured in degrees.

Trueness was defined as the deviation between each test scan and the reference scan, representing accuracy relative to the gold standard. Precision was defined as within-group variability, calculated as the standard deviation of repeated measurements within each group-condition combination.

Clinical acceptability thresholds were defined based on established literature: linear deviations >100 µm and angular deviations >1.0° were considered clinically significant.

3. Observations And Statistical Analysis

All statistical data was coded , proofed for entry errors and compiled in MS office Excel sheets (v2024, Microsoft). Data was subjected to Statistical analysis using Statistical package of social sciences (SPSS) software version 25.0 (IBM Corporation, Armonk, NY, USA).

The following parameters were extracted:

1. Linear Deviations (µm)
2. Mean deviation
3. Root Mean Square (RMS) error
4. Standard deviation
5. Maximum and minimum deviation
6. Euclidean distance:
7. Angular deviation

Table 1. Intergroup Comparison of RMS Error Among Different Scan Body Groups

Cycles	PEEK Compatible Mean ± SD	Titanium Compatible Mean ± SD	Dentium Titanium Mean ± SD	Dentium PEEK Mean ± SD	F value	P value
Cycle 1–2	0.209 ± 0.058	0.166 ± 0.059	0.307 ± 0.520	0.192 ± 0.118	1.284	0.309
Cycle 3–4	0.159 ± 0.047	0.182 ± 0.044	0.130 ± 0.041	0.166 ± 0.069	1.013	0.418
Cycle 5–6	0.188 ± 0.141	0.377 ± 0.215	0.138 ± 0.070	0.137 ± 0.054	5.629	0.004*
Cycle 7–8	0.234 ± 0.137	0.375 ± 0.217	0.045 ± 0.004	0.079 ± 0.033	12.417	<0.001**
Cycle 9–10	0.273 ± 0.139	0.381 ± 0.210	0.073 ± 0.026	0.154 ± 0.023	14.128	<0.001**

Graph 1: RMS error comparison among scan body groups

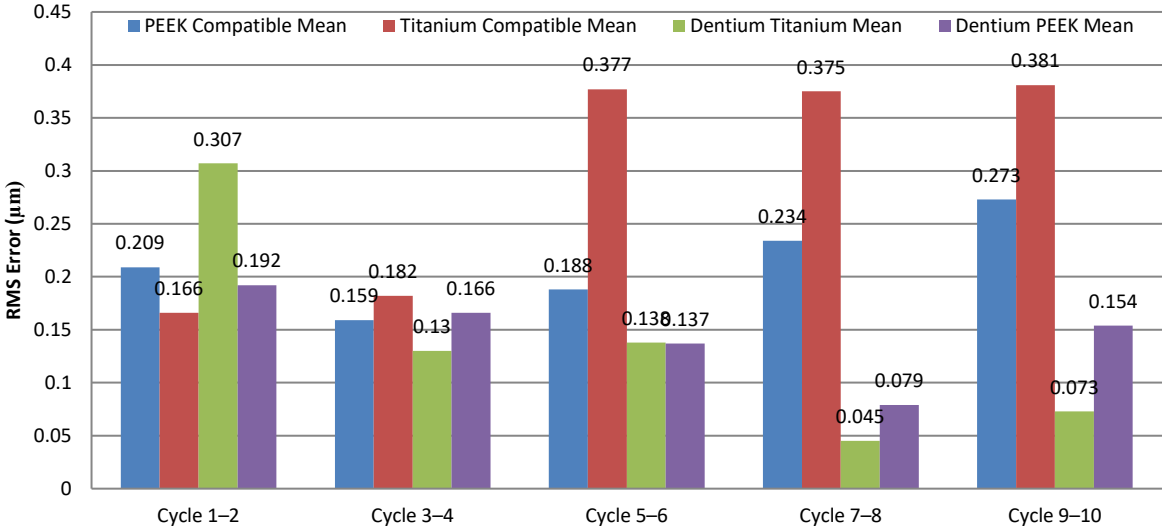

Table 2: Post Hoc Comparison of RMS Error Among Different Scan Body Groups

			Mean Diff	Std Error	P value
Cycle 1-2	Peek Compatible	Titanium Compatible	0.043	0.061	0.624
	Peek Compatible	Dentium Titanium	-0.098	0.091	0.281
	Peek Compatible	Dentium Peek	0.017	0.070	0.973
	Titanium Compatible	Dentium Titanium	-0.141	0.092	0.162
	Titanium Compatible	Dentium Peek	-0.026	0.071	0.921
	Dentium Titanium	Dentium Peek	0.115	0.095	0.218
Cycle 3-4	Peek Compatible	Titanium Compatible	-0.023	0.042	0.844
	Peek Compatible	Dentium Titanium	0.029	0.043	0.772
	Peek Compatible	Dentium Peek	-0.007	0.051	0.998
	Titanium Compatible	Dentium Titanium	0.052	0.042	0.438
	Titanium Compatible	Dentium Peek	0.016	0.052	0.951
	Dentium Titanium	Dentium Peek	-0.036	0.053	0.702
Cycle 5-6	Peek Compatible	Titanium Compatible	-0.189	0.071	0.019*
	Peek Compatible	Dentium Titanium	0.050	0.063	0.618
	Peek Compatible	Dentium Peek	0.051	0.061	0.602
	Titanium Compatible	Dentium Titanium	0.239	0.074	0.002**

	Titanium Compatible	Dentium Peek	0.240	0.073	0.002**
	Dentium Titanium	Dentium Peek	0.001	0.042	1.000
Cycle 7-8	Peek Compatible	Titanium Compatible	-0.141	0.081	0.091
	Peek Compatible	Dentium Titanium	0.189	0.052	<0.001**
	Peek Compatible	Dentium Peek	0.155	0.050	0.002**
	Titanium Compatible	Dentium Titanium	0.330	0.060	<0.001**
	Titanium Compatible	Dentium Peek	0.296	0.058	<0.001**
	Dentium Titanium	Dentium Peek	-0.034	0.032	0.642
Cycle 9-10	Peek Compatible	Titanium Compatible	-0.108	0.078	0.144
	Peek Compatible	Dentium Titanium	0.200	0.049	<0.001**
	Peek Compatible	Dentium Peek	0.119	0.047	0.018*
	Titanium Compatible	Dentium Titanium	0.308	0.057	<0.001**
	Titanium Compatible	Dentium Peek	0.227	0.055	0.001**
	Dentium Titanium	Dentium Peek	-0.081	0.031	0.238

Table 3: Intergroup Comparison of Euclidean Distance Among Different Scan Body Groups

Cycles	PEEK Compatible Mean ± SD	Titanium Compatible Mean ± SD	Dentium Titanium Mean ± SD	Dentium PEEK Mean ± SD	F value	P value
Cycle 1–2	0.194 ± 0.054	0.157 ± 0.056	0.590 ± 0.873	0.180 ± 0.120	1.962	0.148
Cycle 3–4	0.150 ± 0.045	0.169 ± 0.039	0.235 ± 0.064	0.182 ± 0.064	2.814	0.053
Cycle 5–6	0.172 ± 0.124	0.360 ± 0.201	0.239 ± 0.122	0.120 ± 0.041	4.902	0.007*
Cycle 7–8	0.223 ± 0.125	0.369 ± 0.213	0.536 ± 0.180	0.023 ± 0.010	18.352	<0.001**
Cycle 9–10	0.269 ± 0.125	0.366 ± 0.204	0.719 ± 0.224	0.066 ± 0.017	26.229	<0.001**

Graph 2: Euclidean Distance comparison among scan body groups

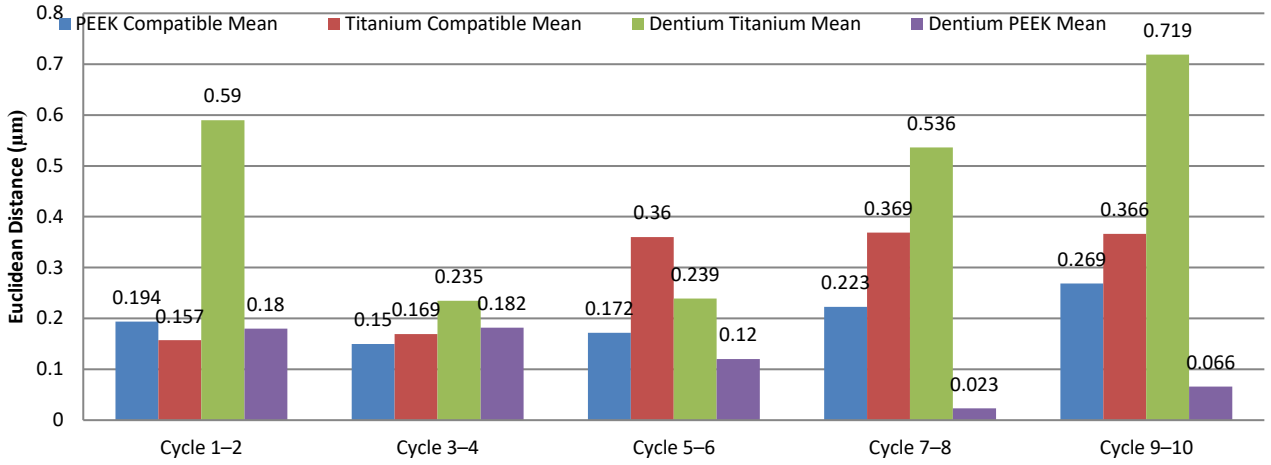

Table 4: Post Hoc Comparison of Euclidean Distance Among Different Scan Body Groups

			Mean Diff	Std Error	P value
Cycle 1-2	Peek Compatible	Titanium Compatible	0.037	0.059	0.701
	Peek Compatible	Dentium Titanium	-0.396	0.171	0.021*
	Peek Compatible	Dentium Peek	0.014	0.082	0.981
	Titanium Compatible	Dentium Titanium	-0.433	0.172	0.010*
	Titanium Compatible	Dentium Peek	-0.023	0.083	0.941
	Dentium Titanium	Dentium Peek	0.410	0.180	0.014*
Cycle 3-4	Peek Compatible	Titanium Compatible	-0.019	0.040	0.912
	Peek Compatible	Dentium Titanium	-0.085	0.048	0.148
	Peek Compatible	Dentium Peek	-0.032	0.049	0.721
	Titanium Compatible	Dentium Titanium	-0.066	0.047	0.232
	Titanium Compatible	Dentium Peek	-0.013	0.049	0.978
	Dentium Titanium	Dentium Peek	0.053	0.055	0.366
Cycle 5-6	Peek Compatible	Titanium Compatible	-0.188	0.069	0.022*
	Peek Compatible	Dentium Titanium	-0.067	0.062	0.304
	Peek Compatible	Dentium Peek	0.052	0.055	0.482
	Titanium Compatible	Dentium Titanium	0.121	0.071	0.049*
	Titanium Compatible	Dentium Peek	0.240	0.067	0.001**
	Dentium Titanium	Dentium Peek	0.119	0.060	0.061
Cycle 7-8	Peek Compatible	Titanium Compatible	-0.146	0.078	0.084
	Peek Compatible	Dentium Titanium	-0.313	0.071	<0.001**
	Peek Compatible	Dentium Peek	0.200	0.046	0.003*
	Titanium Compatible	Dentium Titanium	-0.167	0.073	0.029*

	Titanium Compatible	Dentium Peek	0.346	0.051	<0.001**
	Dentium Titanium	Dentium Peek	0.513	0.048	<0.001**
Cycle 9-10	Peek Compatible	Titanium Compatible	-0.097	0.075	0.314
	Peek Compatible	Dentium Titanium	-0.450	0.069	<0.001**
	Peek Compatible	Dentium Peek	0.203	0.044	0.003*
	Titanium Compatible	Dentium Titanium	-0.353	0.071	<0.001**
	Titanium Compatible	Dentium Peek	0.300	0.049	<0.001**
	Dentium Titanium	Dentium Peek	0.653	0.046	<0.001**

Table 5: Intergroup Comparison of Angular Deviation Among Different Scan Body Groups

Cycles	PEEK Compatible Mean ± SD	Titanium Compatible Mean ± SD	Dentium Titanium Mean ± SD	Dentium PEEK Mean ± SD	F value	P value
Cycle 1–2	0.347 ± 0.098	0.280 ± 0.100	0.727 ± 0.340	0.366 ± 0.288	3.026	0.041*
Cycle 3–4	0.269 ± 0.080	0.303 ± 0.068	0.573 ± 0.189	0.361 ± 0.157	4.884	0.007*
Cycle 5–6	0.309 ± 0.222	0.638 ± 0.364	0.527 ± 0.263	0.234 ± 0.096	5.226	0.005*
Cycle 7–8	0.441 ± 0.203	0.664 ± 0.359	0.111 ± 0.024	0.590 ± 0.173	9.441	<0.001**
Cycle 9–10	0.543 ± 0.216	0.668 ± 0.388	0.175 ± 0.029	0.641 ± 0.216	8.772	<0.001**

Graph 3: Angular Deviation Comparison Among Different Scan Body Groups

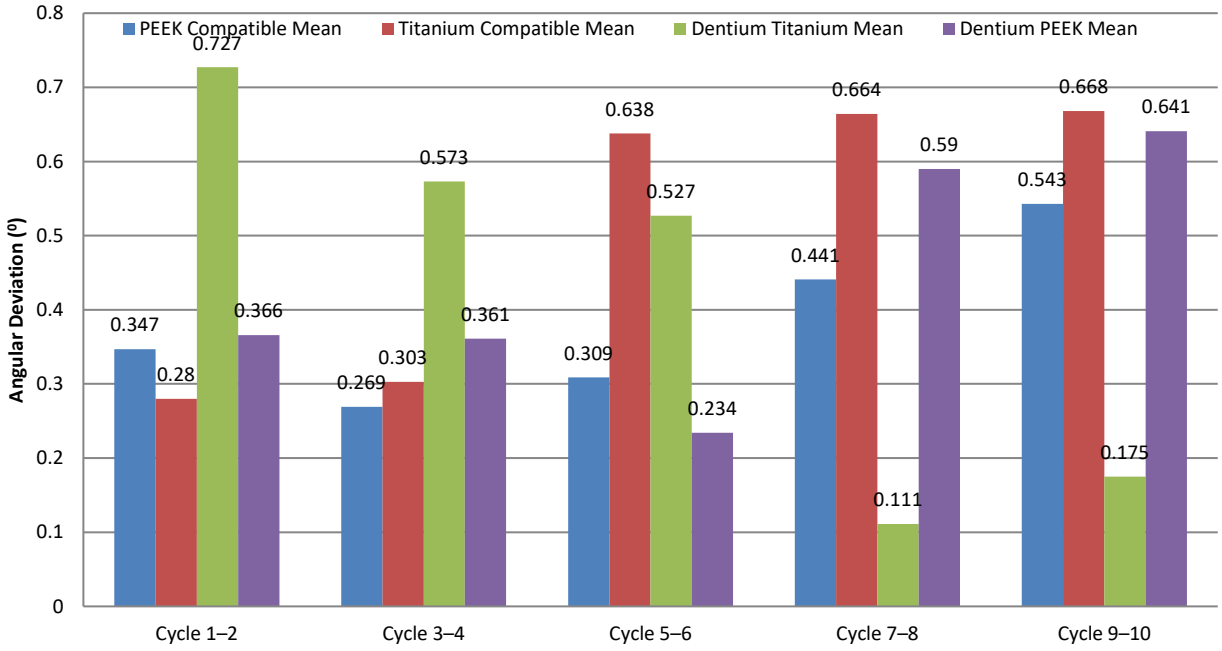

Table 6: Post Hoc Comparison Of Angular Deviation Among Scan Body Groups

			Mean Diff	Std Error	P value
Cycle 1-2	Peek Compatible	Titanium Compatible	0.067	0.073	0.498
	Peek Compatible	Dentium Titanium	-0.380	0.121	0.004*
	Peek Compatible	Dentium Peek	-0.019	0.109	0.972
	Titanium Compatible	Dentium Titanium	-0.447	0.122	0.001**
	Titanium Compatible	Dentium Peek	-0.086	0.110	0.392
	Dentium Titanium	Dentium Peek	0.361	0.131	0.006*
Cycle 3-4	Peek Compatible	Titanium Compatible	-0.034	0.052	0.754
	Peek Compatible	Dentium Titanium	-0.304	0.094	0.009*
	Peek Compatible	Dentium Peek	-0.092	0.082	0.326
	Titanium Compatible	Dentium Titanium	-0.270	0.092	0.014*
	Titanium Compatible	Dentium Peek	-0.058	0.081	0.541
	Dentium Titanium	Dentium Peek	0.212	0.103	0.037*
Cycle 5-6	Peek Compatible	Titanium Compatible	-0.329	0.118	0.012*
	Peek Compatible	Dentium Titanium	-0.218	0.106	0.088
	Peek Compatible	Dentium Peek	0.075	0.084	0.462
	Titanium Compatible	Dentium Titanium	0.111	0.120	0.244
	Titanium Compatible	Dentium Peek	0.404	0.097	<0.001**
	Dentium Titanium	Dentium Peek	0.293	0.093	0.016*
Cycle 7-8	Peek Compatible	Titanium Compatible	-0.223	0.104	0.041*
	Peek Compatible	Dentium Titanium	0.330	0.074	<0.001**
	Peek Compatible	Dentium Peek	-0.149	0.072	0.121
	Titanium Compatible	Dentium Titanium	0.553	0.083	<0.001**
	Titanium Compatible	Dentium Peek	0.074	0.081	0.482
	Dentium Titanium	Dentium Peek	-0.479	0.070	<0.001**
Cycle 9-10	Peek Compatible	Titanium Compatible	-0.125	0.109	0.242
	Peek Compatible	Dentium Titanium	0.368	0.076	<0.001**
	Peek Compatible	Dentium Peek	-0.098	0.073	0.301
	Titanium Compatible	Dentium Titanium	0.493	0.087	<0.001**
	Titanium Compatible	Dentium Peek	0.027	0.084	0.911
	Dentium Titanium	Dentium Peek	-0.466	0.071	<0.001**

Descriptive statistics (mean, standard deviation, range) were calculated for all accuracy metrics.
The inter group comparison was done using One Way ANOVA to find the difference between groups followed by post-hoc Tukey's honestly significant difference (HSD) test for pairwise comparisons. The

intragroup comparison (between scan body groups at each time point) was done using the Paired t test The level of the significance for the present study was fixed at 5%. The Shapiro–Wilk test was used to investigate the distribution of the data and Levene's test to explore the homogeneity of the variables. Statistical significance was set at $\alpha = 0.05$ for all analyses.

4. RESULTS

4.1 Overall Accuracy Trends

Scan body material, manufacturer origin, and repeated sterilization-reuse cycles significantly affected the accuracy of digital implant impressions ($p < 0.05$). All scan body groups demonstrated measurable dimensional alterations following repeated sterilization, though the magnitude and pattern of change varied substantially between materials and manufacturers.

4.2 PEEK Scan Body Performance

PEEK scan bodies (both OEM and third-party) generally exhibited superior dimensional stability across sterilization cycles compared to titanium alternatives.

OEM PEEK Scan Bodies (Group B):

RMS error demonstrated an initial decrease during early cycles, reaching minimum values during cycles 7-8 (0.150 ± 0.045 mm at cycles 3-4), followed by a slight increase in later cycles (0.273 ± 0.139 mm at cycles 9-10). This pattern suggests an initial "settling" period followed by gradual material degradation.

Euclidean distance deviation followed a similar trend, decreasing from 0.194 ± 0.054 mm (cycles 1-2) to 0.150 ± 0.045 mm (cycles 3-4), then increasing to 0.269 ± 0.125 mm (cycles 9-10).

Angular deviation showed the most substantial change, decreasing initially from 0.347 ± 0.098° (cycles 1-2) to 0.269 ± 0.080° (cycles 3-4), then progressively increasing to 0.543 ± 0.216° (cycles 9-10), indicating reduced positional accuracy in advanced reuse cycles.

Third-Party PEEK Scan Bodies (Group D):

Third-party PEEK scan bodies demonstrated comparable dimensional stability to OEM PEEK alternatives, with RMS error values ranging from 0.159 ± 0.047 mm (cycles 3-4) to 0.273 ± 0.139 mm (cycles 9-10). The performance profile closely paralleled that of OEM PEEK scan bodies, suggesting that well-manufactured third-party PEEK components can achieve dimensional fidelity comparable to OEM alternatives.

4.3 Titanium Scan Body Performance

Titanium scan bodies exhibited greater variability in dimensional measurements across sterilization cycles compared to PEEK alternatives.

OEM Titanium Scan Bodies (Group A):

Contrary to expectations, OEM titanium scan bodies showed a decreasing trend in RMS error and Euclidean distance with increasing sterilization cycles, indicating improved dimensional accuracy in advanced reuse cycles. This unexpected finding may reflect progressive surface conditioning or interface optimization through repeated thermal cycling and mechanical connection.

Angular deviation also decreased progressively, suggesting improved rotational stability with repeated use.

Third-Party Titanium Scan Bodies (Group C):

Third-party titanium scan bodies demonstrated progressive increases in all accuracy metrics with repeated sterilization. RMS error increased from 0.166 ± 0.059 mm (cycles 1-2) to 0.381 ± 0.210 mm (cycles 9-10), representing a 129% increase.

Euclidean distance deviation increased from 0.157 ± 0.056 mm (cycles 1-2) to 0.366 ± 0.204 mm (cycles 9-10), indicating progressive positional discrepancy.

Angular deviation showed the most substantial degradation, increasing from 0.280 ± 0.100° (cycles 1-2) to 0.668 ± 0.388° (cycles 9-10), representing a 139% increase and suggesting significant rotational instability in advanced reuse cycles.

4.4 OEM vs. Third-Party Comparison

Intergroup comparisons revealed significant differences between OEM and third-party scan bodies, particularly in advanced reuse cycles:

Cycles 5-6: Third-party titanium scan bodies showed significantly higher RMS error compared to third-party PEEK, OEM titanium, and OEM PEEK groups ($p < 0.05$).

Cycles 7-8: Both third-party groups (titanium and PEEK) showed significantly higher RMS error compared to both OEM groups ($p < 0.05$).

Cycles 9-10: Third-party titanium and third-party PEEK groups showed significantly higher RMS error compared to OEM titanium and OEM PEEK groups ($p < 0.05$).

OEM scan bodies (both titanium and PEEK) generally exhibited lower RMS error values in advanced reuse cycles, indicating superior dimensional accuracy and trueness. However, the difference between OEM and third-party PEEK scan bodies was less pronounced than the difference between OEM and third-party titanium scan bodies, suggesting that material composition may partially compensate for manufacturing tolerance differences.

4.5 Clinical Acceptability

Despite measurable dimensional alterations, all scan body groups maintained deviations within clinically acceptable limits throughout the study Even after ten sterilization cycles, Linear deviations remained well within the 100 µm threshold for clinical acceptability... This finding suggests that controlled reuse of scan bodies up to ten cycles is clinically acceptable from a dimensional accuracy perspective.

Angular deviations showed greater sensitivity to repeated sterilization, particularly for third-party titanium scan bodies, which approached but did not exceed the 1.0° clinical threshold at cycles 9-10 (0.668 ± 0.388°). The higher variability (standard deviation 0.388°) indicates that some individual scan bodies may exceed clinical thresholds, suggesting the need for periodic verification and retirement criteria.

5. DISCUSSION

5.1 Influence of Scan Body Material on Accuracy

One of the most important findings of the present study was the superior dimensional stability demonstrated by PEEK scan bodies compared with their titanium counterparts after repeated sterilization and reuse cycles. This observation suggests that the material properties of scan bodies play a critical role in maintaining digital impression accuracy during repeated clinical use. Previous investigations have emphasized that the physical, optical, and thermal characteristics of scan body materials can significantly influence the accuracy of digital implant workflows.[14,35,38,49]

The favorable performance of PEEK scan bodies may be attributed to their unique physicochemical properties. PEEK exhibits excellent chemical resistance, low water absorption, high dimensional stability, and a glass transition temperature above typical autoclave sterilization temperatures.[33,38,44] Additionally, the thermal conductivity of PEEK is substantially lower than that of titanium, allowing more gradual and uniform heat transfer during sterilization cycles. This characteristic may reduce thermal stress accumulation and minimize dimensional alterations at the implant–scan body interface.[33,38,44]

Another possible explanation for the improved consistency observed with PEEK scan bodies is their optical behavior. The matte, non-reflective surface characteristics of PEEK facilitate more predictable optical scanning and reduce the likelihood of light scattering and reflection artifacts during intraoral data acquisition. Previous studies have demonstrated that optical properties significantly influence scan accuracy and reproducibility, particularly during complete-arch digital implant scanning procedures.[15,16,38,44]

5.2 Effect of Repeated Sterilization and Mechanical Cycling

Although titanium scan bodies possess excellent mechanical strength and wear resistance, the present study demonstrated greater variability in dimensional accuracy following repeated sterilization cycles compared with PEEK scan bodies. Previous studies have reported that repeated thermal and mechanical loading may influence the positional accuracy of implant scan bodies, particularly when sterilization and repeated tightening procedures are combined.38,39,41,42

The higher thermal conductivity of titanium may contribute to rapid heating and cooling during autoclave sterilization, resulting in repeated thermal expansion and contraction at the implant–scan body interface. Over multiple sterilization cycles, these thermal changes may influence seating consistency and contribute to cumulative dimensional variation.[33,38,44]

Interestingly, the system-specific titanium scan bodies demonstrated a slight improvement in accuracy after repeated use. Although the exact mechanism underlying this finding remains unclear, it may be related to progressive stabilization of the implant–scan body interface or elimination of minor manufacturing irregularities after repeated seating and tightening procedures. Similar observations have been reported in studies evaluating mechanical adaptation and precision components; however, further investigations involving surface characterization techniques, such as scanning electron microscopy and surface roughness analysis, are required to confirm this hypothesis.[39,44]

In contrast, third-party titanium scan bodies demonstrated greater dimensional variability after repeated use. This finding may indicate that manufacturing tolerances and connection precision play a more critical role in the long-term performance of titanium scan bodies than previously recognized.31,32,41

5.3 System-Specific versus Third-Party Scan Bodies

An important observation of the present study was the absence of a universal superiority of system-specific scan bodies over third-party alternatives. Although system-specific scan bodies generally demonstrated more consistent performance after repeated sterilization cycles, third-party PEEK scan bodies exhibited accuracy values comparable to those of system-specific components. This finding suggests that material characteristics may compensate, to some extent, for variations in manufacturing tolerances.[14,31,38,44]

The satisfactory performance of third-party PEEK scan bodies may be explained by the favorable thermal and optical characteristics of PEEK, which potentially reduce the impact of minor manufacturing discrepancies. In contrast, titanium scan bodies appear to be more sensitive to variations in manufacturing precision and connection geometry. Consequently, third-party titanium scan bodies exhibited greater variability than their system-specific counterparts after repeated use cycles.[31,32,41,43]

These findings have important clinical implications because they suggest that well-manufactured third-party PEEK scan bodies may represent a clinically acceptable and cost-effective alternative to system-specific scan bodies in selected situations.

5.4 Clinical Relevance

From a clinical perspective, the findings of the present study indicate that repeated sterilization and reuse of implant scan bodies up to ten cycles may not adversely affect digital implant impression accuracy to a

clinically significant extent. Previous studies evaluating digital implant workflows have reported acceptable clinical thresholds for implant impression accuracy and have demonstrated that minor dimensional variations may not necessarily compromise prosthetic outcomes.[11,17,21,37,50]

However, the increased variability observed in certain scan body groups, particularly third-party titanium scan bodies, suggests that clinicians should implement periodic quality control protocols when reusing scan bodies. Such protocols may include visual inspection, assessment of seating accuracy, and periodic verification of digital transfer accuracy after a predetermined number of sterilization cycles.

Another important observation was that angular deviations appeared to be more sensitive to repeated sterilization and reuse than linear deviations. This finding suggests that angular measurements may serve as an early indicator of scan body deterioration and should therefore be considered during quality assessment procedures.[19,25,31]

The superior consistency demonstrated by PEEK scan bodies indicates that these components may be particularly advantageous in practices with high implant workloads and extended reuse protocols. Furthermore, the acceptable performance of third-party PEEK scan bodies supports their potential use as cost-effective alternatives to system-specific components.

5.5 Economic and Environmental Considerations

The possibility of safely reusing implant scan bodies has important economic and environmental implications. Repeated use of scan bodies may substantially reduce treatment costs by decreasing the frequency of replacement and lowering inventory requirements. Previous investigations have demonstrated that digital workflows can significantly reduce treatment costs while improving efficiency.[18,37,46]

In addition to economic benefits, extending the service life of scan bodies may contribute to environmentally sustainable dental practice by reducing material consumption, packaging waste, and the environmental burden associated with manufacturing and disposal processes. As sustainability becomes increasingly important in healthcare systems, controlled reuse protocols may provide both economic and environmental advantages.

Nevertheless, economic considerations should not compromise clinical accuracy. Therefore, any reuse protocol should be accompanied by appropriate verification procedures to ensure maintenance of dimensional accuracy throughout the lifespan of the scan body.

5.6 Limitations of the Study

Several limitations of the present study should be considered when interpreting the findings. First, the investigation was conducted under in vitro conditions using a standardized master model. Clinical situations involve numerous additional variables, including saliva, soft tissue mobility, patient movement, and operator-related factors, which may influence digital impression accuracy differently.[4,5,24,37,45]

Second, only one implant system with an internal hex connection was evaluated. Different implant systems and connection geometries may demonstrate different responses to repeated sterilization and reuse protocols.

Third, only steam autoclave sterilization was investigated. Alternative sterilization methods, such as chemical sterilization or dry heat sterilization, may produce different effects on scan body dimensional stability.

Fourth, the present study evaluated a maximum of ten sterilization cycles. Although this number reflects common clinical practice, the long-term effects of more extensive reuse remain unknown and require further investigation.

Fifth, the effect of different tightening torque values was not evaluated. Because tightening torque can influence scan body seating accuracy and component wear, future studies should investigate the effect of varying torque values on dimensional stability.[27,39]

Finally, only titanium and PEEK scan bodies were investigated. Other materials, including zirconia and fiber-reinforced polymer materials, may demonstrate different thermal and mechanical behaviors and should be evaluated in future studies.

6. CONCLUSION

Within the limitations of this in vitro study, it can be concluded that the accuracy of digital implant impressions is influenced by a combination of scan body material, manufacturer origin, and repeated sterilization-reuse cycles. Among these factors, the material composition of the scan body demonstrated a greater effect on dimensional accuracy than manufacturer origin. PEEK scan bodies exhibited superior dimensional stability, greater consistency, and reduced variability throughout repeated sterilization cycles when compared with titanium scan bodies, indicating that their favorable thermal, mechanical, and optical properties contribute to enhanced performance.

Repeated sterilization and reuse up to ten cycles produced measurable changes in dimensional accuracy; however, these alterations did not result in clinically unacceptable deterioration of scan body performance. The findings suggest that controlled reuse of implant scan bodies can be considered clinically feasible when appropriate sterilization and quality assurance protocols are followed. Although system-specific scan bodies generally demonstrated better reproducibility after repeated use, well-manufactured third-party PEEK scan bodies achieved accuracy comparable to their system-specific counterparts, challenging the conventional assumption that third-party components are inherently inferior.

The study also demonstrated that angular deviations tended to increase more noticeably than linear deviations with repeated use, indicating that angular measurements may serve as a more sensitive parameter for detecting early scan body deterioration. These findings highlight the importance of implementing structured reuse protocols that include baseline verification, periodic accuracy assessment, and clearly defined replacement criteria to maintain predictable clinical outcomes.

From a clinical and economic perspective, PEEK scan bodies, particularly high-quality third-party alternatives, appear to provide a reliable and cost-effective option for digital implant workflows involving multiple implant systems. Overall, the findings of this study provide evidence-based guidance for the selection and reuse of implant scan bodies in digital dentistry. Further research should investigate the effects of extended reuse beyond ten sterilization cycles, evaluate different implant systems and connection geometries, and validate these findings under clinical conditions to establish comprehensive recommendations for routine practice.

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