Keywords
Enhanced scan; original scan; precision; polyetheretherketone; narrow diameter; regular diameter

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An in vivo Study on the Accuracy of Digital Implant Impressions

ABSTRACT
Background: Digital dental implant impressions are advancing implant dentistry, but in vivo evidence remains scarce. This in vivo study evaluated the precision of digital implant impressions using narrow- (ND) and regular-diameter (RD) polyetheretherketone (PEEK) implant scan bodies (ISBs), comparing original intraoral scans with enhanced datasets. Methods: A maxillary partially edentulous patient received two ND and two RD bone-level implants. After healing, manufacturer-specific PEEK ISBs were connected, and five full-arch digital impressions were captured using an intraoral scanner (IOS). Each original scan was duplicated and enhanced by replacing the scanned ISB meshes with library files. Forty three-dimensional (3D) comparisons were performed using metrology software, and root mean square (RMS) values quantified precision. Data were analyzed using descriptive statistics and the non-parametric Mann–Whitney U test ($\alpha = 0.05$). Results: Enhanced scans demonstrated higher precision than original scans (mean RMS: ND 29.87 µm; RD 28.96 µm vs. ND 85.93 µm; RD 127.22 µm; $p < .05$). ISB diameter showed no significant effect ($p > .05$). Conclusion: Original scans exhibited lower precision, but they were adequate for library files alignment and generation of enhanced scans that were approximately 65–77% more precise. Enhanced scans provide clinically acceptable digital implant impression accuracy.

INTRODUCTION

Digital workflows have revolutionized clinical dentistry over the past two decades, offering greater efficiency, improved patient comfort, and enhanced communication between clinicians, dental technicians, and patients. Within restorative and implant dentistry, the integration of intraoral scanning, computer-aided design (CAD), and computer-aided manufacturing (CAM) technologies has significantly streamlined diagnostic, planning, and fabrication processes.[1] Among these, digital impressions, captured directly with intraoral scanner (IOS), eliminate the need for conventional impression materials, reducing potential errors from material deformation, disinfection, and gypsum cast pouring.[2, 3]

In implant dentistry, digital impressions are obtained through intraoral scanning of specific components known as implant scan bodies (ISBs). These devices, temporarily connected to the implant or abutment, serve as reference geometries that allow the implant's three-dimensional position and orientation to be transferred to a virtual model. The accuracy of the digital implant impression, and thus the fit of the final prosthesis, relies heavily on the precision of ISB scanning and subsequent matching to their CAD library files.[4]

A substantial body of in vitro research has evaluated the accuracy of digital implant impressions under controlled laboratory conditions. Many studies have examined variables such as ISB geometry, material, implant angulation, and scanner technology.[5-7] For instance, one study reported that varying ISB material and diameter significantly affected precision.[8] Similarly, another studies demonstrated that scan body design impacts the transfer accuracy of implant position.[9, 10] These laboratory-based findings provide valuable insight but may not fully reflect the challenges of the intraoral environment.

In contrast, in vivo studies on digital implant impressions remain comparatively scarce. A recent systematic reviews identified only a limited number of clinical investigations compared with the wealth of in vitro research.[11, 12] Some studies have evaluated full-arch and partially edentulous cases, reporting reduced accuracy in vivo, attributable to patient- and operator-related variables.[13-15] It was noted that while modern IOSs can achieve clinically acceptable accuracy,[12] the variability is greater than in laboratory settings.[15] Collectively, the limited clinical evidence underscores the need for more comprehensive in vivo assessments, especially when evaluating the influence of ISB design and scan enhancement strategies.

Differences in methodology can also influence reported outcomes. Some studies evaluate raw "original" scan data directly from the IOS,[8] while others use processed "enhanced" datasets in which the scanned ISB mesh is aligned with and replaced by its CAD library geometry before analysis.[16] Such differences may affect precision values and comparability between studies.[17] Nevertheless, several measurement methods have been employed to evaluate the accuracy of digital implant impressions that only adds to heterogeneity between studies.[5, 16, 18, 19] One documented measurement approach is superimposition analysis using 3D inspection software, which allows for a quantitative comparison of point clouds or surface meshes and generates deviation maps and computes numerical indices such as root mean square (RMS).[8]

The present in vivo study aimed to assess the precision of digital implant impressions using narrow-diameter (ND) and regular-diameter (RD) polyetheretherketone (PEEK) ISBs, comparing original and enhanced scan datasets. The following null hypotheses were tested, H_{0i}: there would be no differences in the precision between the ND and RD ISBs groups when using the original scans; H_{0ii}: there would be no differences in the precision between the ND and RD ISBs groups when using the enhanced scans; H_{0iii}: there would be no differences in the precision between the original and enhanced scan groups when using the ND ISBs; H_{0iv}: there would be no differences in the precision between the original and enhanced scan groups when using the RD ISBs.

MATERIALS AND METHODS

Ethical Approval and Clinical Case Selection

The research protocol for this investigation was reviewed and approved by the Standing Committee of Bioethics Research (SCBR) at Prince Sattam bin Abdulaziz University, Deanship of Scientific Research, Saudi Arabia (approval no. SCBR-119/2023). A suitable partially edentulous patient was identified, presenting with bilateral posterior maxillary tooth loss involving the second premolars and first molars (Kennedy Class III with modification 1). The treatment plan included surgical placement of four dental implants to restore the edentulous spaces. Two narrow-diameter (Ø 3.3 mm) and two regular-diameter (Ø 4.1 mm) bone-level implants (Straumann Roxolid, Bone Level Implant; Straumann, Basel, Switzerland) were placed in the second premolar and first molar sites, respectively, using a conventional two-stage surgical approach. Following an uneventful healing period, second-stage surgery was performed to uncover the submerged fixtures, after which manufacturer-specific healing abutments were connected to each implant to facilitate peri-implant tissue maturation prior to scanning.

Implant Scan Bodies and Intraoral Scans

Manufacturer-recommended PEEK implant scan bodies (ISBs) were used for this study. Two ND ISBs (Straumann CARES Mono Scanbody, REF 025.2915) and two RD ISBs (Straumann CARES Mono Scanbody, REF 025.4915; Straumann, Basel, Switzerland) were mounted onto the corresponding ND and RD implant fixtures. After verifying correct seating and screw tightening torque according to manufacturer guidelines, intraoral scanning was performed. Five complete-arch scans were acquired by a single experienced operator using a parallel confocal microscopy-based intraoral scanner (iTero Element 5D imaging system; Align Technology, Inc., Tempe, Arizona, USA). Each scan followed the same standardized acquisition sequence to ensure consistency, and the resulting datasets were saved in Standard Tessellation Language (STL) format (Figure 1).

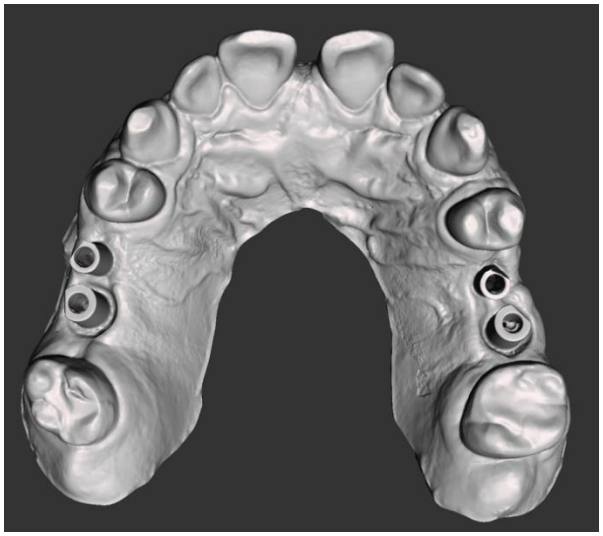

Figure 1. A representative intraoral scan with ND and RD ISBs attached.

Original Versus Enhanced Scans

Each of the five original STL datasets was duplicated to create a working copy for enhancement. The duplicate files were imported into a compatible dental computer-aided design (CAD) software (exocad DentalCAD; Align Technology, Inc., Tempe, Arizona, USA), where the scanned geometry of each ISB was first aligned with its corresponding manufacturer-provided ISB CAD file from the official library. Following this alignment process, the scanned ISB mesh was digitally replaced

with the exact CAD library geometry. This procedure was repeated for all five scans, resulting in a second dataset, the enhanced scans, comprising ISBs represented entirely by their CAD library geometry.

3D Comparisons and RMS Value Calculations

All scans were first cleaned with the help of a mesh-editing software (Meshmixer; Autodesk, Inc., San Rafael, California, USA) to eliminate any unnecessary part of the scans, keeping the data of teeth and ISB necessary to analysis. The datasets were then evaluated by importing them to a 3D inspection and metrology software (CloudCompare; Open-source project, Paris, France). In every comparison, two scans were imported simultaneously, segmented, and aligned using both ISBs and teeth data to establish the best-fit superimposition. Once aligned, only the ISB data were selected for the deviation analysis. The software calculated the differences between the two datasets, and the root mean square (RMS) value was recorded for each comparison as a measure of the magnitude of all deviations, irrespective of direction. A total of 40 (N) pairwise comparisons were performed across four experimental groups (n = 10 per group), which were used to test the four null hypotheses. Figures 2 and 3 present the grouping workflow and corresponding hypotheses, respectively.

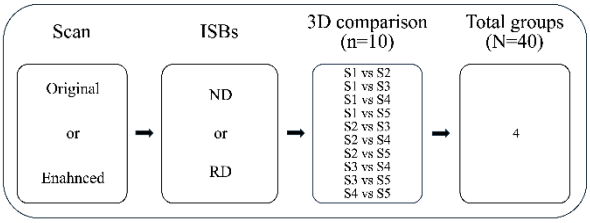

Figure 2. Flow chart for formation of the study groups.

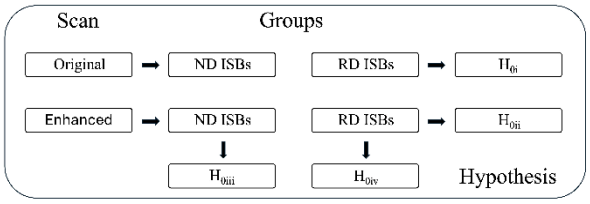

Figure 3. Flow chart for formation of the study null hypotheses.

Accuracy Definitions

According to the International Organization for Standardization (ISO) 5725, the accuracy of a measurement method is described by two components: precision and trueness. Precision refers to the closeness of agreement between repeated measurements under the same conditions, while trueness refers to the closeness of agreement between the mean of a large number of measurements and the true or accepted reference value. Previous research has shown that reference scanners, although reported by manufacturers to have high accuracy, can be affected by test conditions, making them less reliable for trueness evaluation.[8] In addition, in vivo trueness assessment requires taking a conventional impression and digitizing it with a reference scanner, a process that introduces additional sources of error. For these reasons, the present study assessed accuracy exclusively in terms of precision.

Software Validation, Sample Size and Statistical Analysis

The 3D inspection and metrology software was validated following the same procedure described in previous study.[8] Duplicate scans were compared, yielding RMS values of 0 µm, confirming complete measurement accuracy of the software. Sample size determination, based on the same reference study, indicated that 10 comparisons per group were required to achieve 80% statistical power (α = 0.05). Because RMS values are derived from squared deviations, normal distribution of the data was not assumed. Hence, non-parametric inferential statistics (Mann–Whitney U test) were performed in addition to descriptive statistics, with the significance level set at α = 0.05, using the statistical software package (IBM SPSS Statistics, version 25; IBM Corp., Armonk, NY, USA).

RESULTS

The mean, standard deviation, and median RMS values of the groups of 3D comparisons used to test the precisions of the original or enhanced scans with ND or RD ISBs groups are illustrated in table 1. The enhanced scan groups recorded lower mean and median RMS values than the original scan groups. Boxplots of the precision RMS values for the four groups are presented in figure 4. Narrower distributions were noted among the enhanced scan groups in comparison to original scan groups regardless of the ISB diameter. The first two null hypotheses comparing ND and RD ISBs across both scan categories were retained since no statistical differences were detected. Similar performances were noted when comparing ND ISBs to their RD

Table 1. Mean, standard deviation (SD) and median values for the root mean square (RMS) values (µm) for the four study groups.

Original scan			Enhanced scan		
Group	**Mean (SD)**	**Median**	**Group**	**Mean (SD)**	**Median**
ND ISBs	85.93 (28.4)	79.81	ND ISBs	29.87 (9.55)	30.65
RD ISBs	127.22 (65.06)	102.31	RD ISBs	28.96 (9.02)	29.93

ISB, implant scan body. ND, narrow diameter. RD, regular diameter.

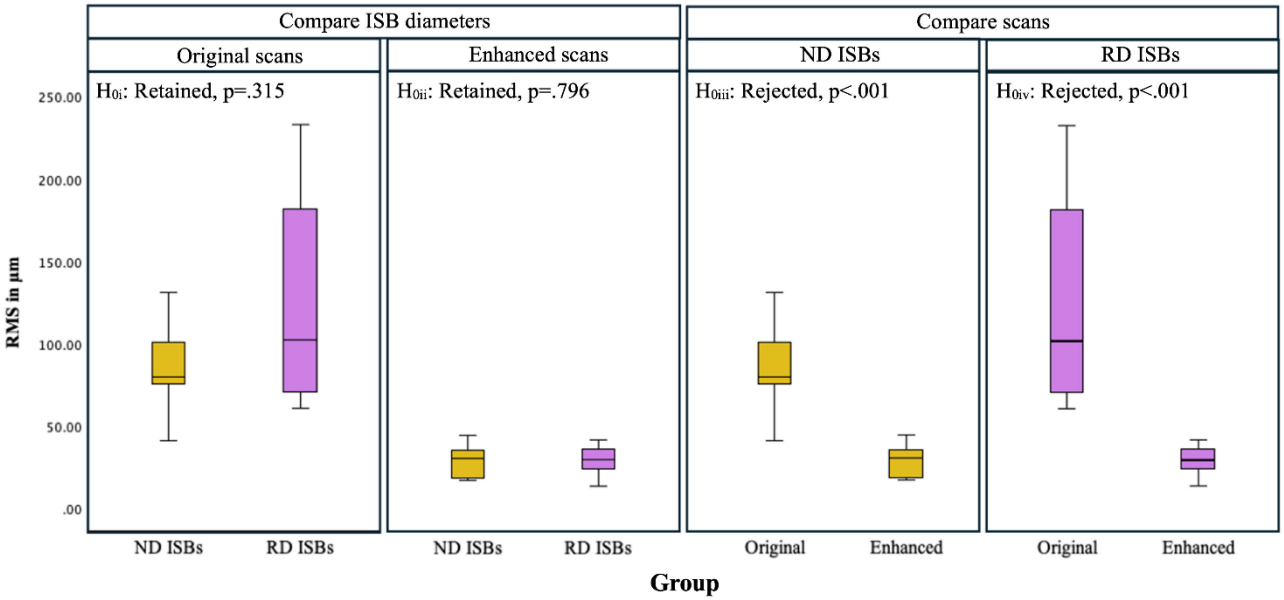

Figure 4. Boxplot of the groups used to test the precision of the digital implant impressions. Nonparametric Mann–Whitney U test statistics probability values, p, are displayed (α=.05).

counterparts. When comparing the original scan versus the enhanced scans, statistically significant differences were detected (p <.05) leading to the rejection of third and fourth null hypotheses. The enhanced scan groups had the highest precisions when compared to the original scan groups.

DISCUSSION

This in vivo study evaluated the precision of digital implant impressions captured with ND and RD PEEK ISBs, comparing original IOS datasets with enhanced datasets in which the scan-derived ISB mesh was replaced by the corresponding CAD library geometry. The results revealed no statistically significant differences in precision between ND and RD ISBs in either scan category, but a clear and statistically significant improvement in precision when enhanced scans were used, regardless of ISB diameter.

The numerical differences were substantial. For original scans, ND ISBs recorded a mean RMS deviation of 85.93 µm, whereas RD ISBs recorded 127.22 µm, with both exhibiting relatively wide variability (SD 28.4 µm and 65.06 µm, respectively). After enhancement, precision improved markedly, with mean RMS values reduced to 29.87 µm for ND and 28.96 µm for RD, and variability narrowed considerably (SD 9.55 µm and 9.02 µm, respectively). These improvements, coupled with tighter distributions, indicate that the enhancement process not only reduced overall deviation but also increased reproducibility.

Despite variations in study design and the type of IOS employed, the findings of current study aligns with the findings of a previous study which reported better but not statistically significant performance of ND PEEK ISBs compared to RD counterparts.[8] This trend suggests a potential advantage in precision for the ND PEEK ISBs. However, this difference was evident only in the original scans, as the application of scan enhancement techniques tended to reduce RMS values and obscure differences between the two groups. In the present study, the enhancement process reduced RMS deviations by approximately 65–77% relative to original scans. This magnitude of improvement is clinically relevant, as lower deviations in ISB registration translate directly into better-fitting restorations, potentially reducing screw loosening, prosthetic misfit, and peri-implant stress.[20, 21]

Variability in methodological approaches across studies specifically whether analyses are based on original or enhanced datasets may account for part of the heterogeneity in reported accuracy outcomes. Studies limited to original scans may underestimate the achievable precision of a given IOS system,[8] whereas those employing library replacement likely report optimized performance values.[16] Given the large discrepancy in RMS values observed between scan types in this study, it is essential for future research to explicitly state which methodology is used.

Clinically, the enhancement step, specifically the alignment of the scanned ISB mesh with the corresponding CAD library file in the design software, is not an optional refinement but a mandatory step in any digital implant workflow to enable prosthetic design. The present findings highlight that, despite the lower precision of the original scans, they were sufficiently accurate to permit successful alignment of library files resulting in enhanced digital impressions with high precision. However, this observation is specific to the presented partially edentulous case and may not be directly generalizable to other clinical scenarios, such as full-arch, highly angulated or deeply placed implant cases, without further investigation.

CONCLUSIONS

In the constraints of this in vivo experiment, the precision of digital implants impressions did not differ significantly with the ISB diameter using original or enhanced scans. Nonetheless, when the scanned ISB

mesh is substituted by the corresponding CAD library geometry, the precision was enhanced by almost 65 and 77% in ND and RD ISBs, respectively, and the mean RMS deviations were cut down to lower than 30µm. Although original scans demonstrated lower precision, they were adequate to enable successful library alignment and generation of highly precise enhanced scans. These findings emphasize the importance of reporting scan processing methodology in digital implant accuracy studies.

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