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# Accuracy of full-arch prostheses fabricated through fully digital, hybrid or conventional workflows: A 3D superimposition analysis

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**Abstract:**
Achieving passive and accurate fit of full-arch implant-supported prostheses remains challenging because cumulative fabrication errors can compromise clinical outcomes. Therefore, it is of interest to compare the trueness and precision of full-arch prostheses fabricated using fully digital, hybrid and conventional workflows. Thirty maxillary full-arch frameworks (n = 10/group) were fabricated on a six-implant reference model and evaluated using three-dimensional superimposition, linear interimplant discrepancy and single-screw passive-fit testing. The fully digital workflow demonstrated the highest trueness and precision (41.8 ± 8.6 μm), followed by the hybrid (58.7 ± 10.9 μm) and conventional (86.4 ± 18.7 μm) workflows, with significant intergroup differences ($p < 0.001$). Thus, data shows that fully digital workflow produced the most accurate and reproducible prostheses, while the hybrid workflow was a clinically reliable alternative to the conventional technique.

**Keywords:** Digital workflow, full-arch prosthesis, implant prosthodontics, trueness, precision, computer-aided design /computer-aided manufacturing (CAD/CAM)

**Background:**
Full-arch implant-supported prosthetic rehabilitation is a very technique-sensitive procedure in which the biological and mechanical outcomes are influenced by the passivity of the prosthesis, spatial accuracy, occlusal harmony and adaptation of the framework. Any misalignment of the implant position and the intaglio surface of the definitive prosthesis can generate screw-joint stress, marginal misfit, veneering problems, fracture of the definitive prosthesis, screw loosening or peri-implant tissue strain. Therefore, the shift from analog to digitally assisted and fully digital workflow has become a major theme in modern prosthodontics **[1]**. The accuracy of a full-arch prosthesis is typically expressed in two different but similar terms: trueness and precision. Trueness is the degree of agreement between a test object and a reference or master model, while precision is the degree of agreement among several objects that are produced by the same process. In full-arch implant prosthodontics both parameters are clinically relevant. A workflow can yield a prosthesis that is close to the reference model, but has poor repeatability, or it can yield consistent results that are systematically different from the desired reference. The root mean square deviation, mean absolute deviation, maximum deviation and localized color-map evaluation can be used to quantify both dimensions of accuracy in three-dimensional superimposition analysis **[2]**. The traditional method for making a full-arch prosthesis typically requires open-tray implant-level impressions, splinting of impression copings, elastomeric materials, definitive cast pouring, verification jigs, wax or resin pattern making, investing, casting or milling and laboratory remounting. This method is well known and used by clinicians and technicians, but there are several steps where distortion can occur: polymerization shrinkage of splinting resin, impression material strain, analog displacement, stone expansion and inaccuracies during the processing of the framework **[3]**. The goal of fully digital workflows is to minimize these cumulative errors by using intraoral scanning to capture implant positions, transferring the digital scan-body geometry to computer-aided design software and manufacturing the definitive framework using subtractive or additive computer-aided manufacturing. The benefits of digital systems are: reduced chairside time, simplified data storage, communication with the lab is easier and virtual design procedures are repeatable. Full-arch scanning is more challenging than short-span scanning, however, due to the lack of stable landmarks in edentulous mucosa, the geometry of the scan may be influenced by the angulation and interimplant distance and stitching errors may increase with longer scan path **[4]**. Hybrid workflows are a mix of analog and digital processes. This can include traditional impressions and cast scanning, digitally designed frameworks from scanned verification casts, or intraoral scanning and analog verification. The hybrid pathways are popular in clinical practice as they enable the clinician to maintain the traditional analog impression techniques and still gain the advantages of computer-aided design and manufacturing. For full-arch cases, the hybrid

approach can be especially beneficial when obtaining a complete digital acquisition is challenging, but when the production of a digital framework is more standardized than traditional casting or hand finishing **[5]**. Recent studies have shown that the accuracy of the full-arch impression and the prosthetic components depends on the type of scanner, the scanning strategy, the number of implants, the distance between the implants, the design of the scan body, the angulation of the implants, the depth of the implants, the operator experience and the superimposition method. Selected intraoral scanners have been shown to have better trueness than conventional impressions in some *in vitro* studies, while others have demonstrated that conventional impressions in complete-arch implant scenarios are still very reliable. Systematic reviews also highlight the differences in measurement protocols, reference datasets and outcome definitions, which make it difficult to compare studies directly **[6]**. Three-dimensional superimposition analysis has enhanced the objective evaluation of digital and conventional workflows. When a scanned prosthesis dataset is aligned to a reference dataset, deviations can be displayed and measured over the entire surface of the prosthesis. This approach is more informative than a linear measurement alone as full-arch frameworks can present with rotational distortion, localized palatal or buccal displacement, cantilever deviation, or uneven intaglio surface adaptation that is not detected by two-dimensional measurements. Furthermore, colour coded deviation maps give clinically interpretable information about the location of overextension or under fit **[7]**. Although digital implant dentistry has advanced significantly, there is limited information available that compares the trueness and precision of final full-arch prostheses produced using fully digital, hybrid and conventional workflows, using the same reference model and same 3D superimposition protocol. Most studies have been conducted on the accuracy of the impression or on the performance of the scanner, but not on the overall accuracy of the entire prosthesis fabrication process. This gap is clinically significant because it is the sum of the errors made in acquisition, design and manufacturing of the prosthesis, not the sum of the errors in any one of these steps **[8]**. Therefore, it is of interest to compare the trueness and precision of maxillary full-arch implant-supported prostheses produced via fully digital, hybrid and conventional workflows, using 3D superimposition analysis.

## Materials and Methods:

### Study design:

An *in vitro*, comparative study was performed in a prosthodontic research laboratory using a standardized maxillary edentulous reference model with six implant analogs placed to simulate a full-arch implant-supported fixed prosthesis.

### The study was divided into three fabrication workflows:

Group A (fully digital workflow), Group B (hybrid workflow) and Group C (conventional workflow). The main outcome was trueness, defined as the root mean square deviation of each fabricated prosthesis dataset from the reference prosthesis dataset following 3D best fit superimposition. Secondary outcomes included precision, linear discrepancy between the implants, maximum surface deviation and single-screw passive-fit gap.

### Sample size:

The sample size was determined based on preliminary pilot data indicating a minimum difference of 25 μm between groups with a pooled standard deviation of 15 μm. A minimum of 8 specimens per group was needed for an alpha level of 0.05 and 80% power. In order to account for potential processing errors and to enhance the robustness of the comparisons, 10 prostheses were created for each group, giving a total of 30 full-arch prostheses.

### Reference model:

A maxillary edentulous epoxy resin model was fabricated, which contained six internal-connection implant analogs in the right first molar, right first premolar, right lateral incisor, left lateral incisor, left first premolar and left first molar regions. The clinically realistic ranges of implant angulations (0 to 17 degrees) were placed. The reference STL dataset was obtained using a high accuracy industrial scanner. This data set was used as the reference for all 3D comparisons.

### Inclusion and exclusion criteria:

Prostheses were included if the 6 implant interfaces were fully seated, screw channels were undamaged and the STL dataset scanned was free of visible artifacts. Prostheses were excluded if they were manufactured faulty, fractured during finishing, did not seat correctly on the reference model, did not match the scan-body, were corrupted or had any visible defect that would not allow for reliable superimposition.

### The fully digital workflow:

The bodies were scanned and then tightened on the reference model with a standardized torque of 10 Ncm. The intraoral scanner was calibrated and then scanned the arch using a continuous zig-zag scanning path from the right posterior region to the left posterior region, along with capturing the occlusal, buccal and palatal surfaces. The scan data were transferred to the dental CAD software and a screw-retained full-arch titanium framework with equal thickness and standardized connector size was designed. The five-axis milling unit was used to mill frameworks from pre-sintered titanium blanks.

### Hybrid workflow:

Open-tray splinted impressions were taken with addition silicone impression material. Impression copings were splinted with low-shrinkage autopolymerizing resin, sectioned after initial polymerization and then rejoined after 10 minutes to minimize polymerization distortion. Definitive casts were made using type IV dental stone. Each cast was scanned with a laboratory scanner and the prosthetic framework was digitally designed and milled with the same design parameters and manufacturing unit as the fully digital group.

**Conventional workflow:**
Open-tray splinted impressions and definitive casts were made using the same analog protocol as the hybrid group. The workflow of conventional resin pattern, investing, casting, finishing and polishing was used to fabricate the frameworks. A silicone index was created from the reference design and the same prosthetic design dimensions were reproduced. To minimise operator variability, all conventional frameworks were completed by one experienced technician.

**Superimposition and 3D scanning:**
Each of the fabricated prostheses was scanned in the same laboratory scanner, after the application of scanning spray if necessary. The STL datasets were loaded into metrology software. The test prostheses were aligned to the reference prosthesis dataset using an initial landmark alignment and then a best fit surface registration.

**The following deviations were recorded:**
Root mean square deviation, Mean absolute deviation, Positive maximum deviation, Negative maximum deviation and Color-coded deviation distribution. For trueness, each prosthesis was compared with the reference dataset. To ensure precision, pairwise comparisons were made within each group and the mean intra-group deviation was computed. Interimplant and passive-fit evaluation: STL datasets were used to measure the distances between the terminal implant interfaces (interimplant) and the cross-arch diagonal distances (passive-fit). Single screw test was used to evaluate passive fit. The prostheses were tightened at the correct terminal implant and the vertical gap was determined at the remaining five implant interfaces with a stereomicroscope at 40x magnification. This was repeated with the left terminal implant tightened and the mean passive-fit gap was determined.

**Data analysis:**
Statistical software was used for data analysis. The Shapiro-Wilk test was used to determine normality and Levene test was used to determine homogeneity of variance. Normally distributed continuous variables were analyzed using one-way analysis of variance and then Tukey post-hoc testing. The Kruskal-Wallis test and Dunn post hoc comparisons were used for non-normally distributed variables. The chi-square test was used to compare categorical distribution of deviation zones. A significance level of $p < 0.05$ was used.

**Results:**
Thirty full-arch prostheses were finally analyzed, 10 prostheses in each workflow group. There were no files that were corrupted or manufactured that were excluded. The reference model demonstrated good scan repeatability and all STL datasets were appropriate for superimposition. The accuracy of descriptive values was consistent, with the fully digital workflow having the lowest deviations, followed by the hybrid workflow and then the conventional workflow. Significant differences were found between the three workflows by trueness analysis. The mean root mean square deviation was 41.8 ± 8.6 µm in the fully digital group, 58.7 ± 10.9 µm in the hybrid group and 86.4 ± 18.7 µm in the conventional group ($p < 0.001$). The post-hoc comparisons revealed significant differences between fully digital and hybrid workflows ($p = 0.018$), fully digital and conventional workflows ($p < 0.001$) and hybrid and conventional workflows ($p = 0.002$). The deviations from the mean were also the highest in the conventional group, both positive and negative. Precision was also similar. The mean pairwise deviation within the fully digital group was 27.6 ± 5.4 µm, whereas that within the hybrid group was 39.8 ± 7.2 µm and within the conventional group was 61.9 ± 12.6 µm ($p < 0.001$). The conventional workflow exhibited greater variation in repeated prostheses while the fully digital workflow produced the most consistent prostheses. The repeatability of the hybrid workflow was intermediate and the variability was lower than the conventional workflow. The fully digital group had the lowest linear discrepancies between implants and the conventional group had the highest. The terminal cross-arch discrepancy measured 37.4 ± 8.1 µm for fully digital, 52.6 ± 9.7 µm for hybrid and 79.2 ± 16.8 µm for conventional workflows ($p < 0.001$). The mean vertical gap values were 24.9 ± 6.2 µm, 35.8 ± 7.4 µm and 58.6 ± 13.1 µm in the fully digital, hybrid and conventional groups, respectively ($p < 0.001$) for passive-fit analysis. The results of color map distribution revealed that 82.4% of the surface area in the fully digital group was within ±50 µm, while 70.1% and 54.8% of the surface area in the hybrid and conventional groups, respectively, and were within the same range. The deviations from the conventional group were primarily localized at the implant interfaces at the terminal end and at the distal end of the cantilever, whereas the surface adaptation of the fully digital group was more uniform **(Table 1-3).**

**Table 1:** Comparison of trueness parameters among full-arch prosthesis workflows

| Parameter | Fully digital (n=10) | Hybrid (n=10) | Conventional (n=10) | p-value |
|---|---|---|---|---|
| **RMS deviation (µm)** | 41.8 ± 8.6 | 58.7 ± 10.9 | 86.4 ± 18.7 | <0.001 |
| **Mean absolute deviation (µm)** | 33.2 ± 6.7 | 47.5 ± 9.4 | 71.6 ± 15.2 | <0.001 |
| **Maximum positive deviation (µm)** | 118.5 ± 21.4 | 151.3 ± 28.7 | 219.8 ± 43.5 | <0.001 |
| **Maximum negative deviation (µm)** | -106.7 ± 18.9 | -139.2 ± 25.6 | -204.4 ± 39.8 | <0.001 |
| **Surface within ±50 µm (%)** | 82.4 ± 6.1 | 70.1 ± 7.8 | 54.8 ± 10.6 | <0.001 |

*RMS: root mean square. Values are expressed as mean ± standard deviation.*

**Table 2**: Precision and linear discrepancy measurements among workflows

| Parameter | Fully digital (n=10) | Hybrid (n=10) | Conventional (n=10) | p-value |
|---|---|---|---|---|
| **Pairwise precision deviation (µm)** | 27.6 ± 5.4 | 39.8 ± 7.2 | 61.9 ± 12.6 | <0.001 |
| **Terminal cross-arch discrepancy (µm)** | 37.4 ± 8.1 | 52.6 ± 9.7 | 79.2 ± 16.8 | <0.001 |

| | | | | |
|---|---|---|---|---|
| **Anterior interimplant discrepancy (μm)** | 24.8 ± 6.0 | 34.7 ± 7.9 | 49.9 ± 11.3 | <0.001 |
| **Posterior interimplant discrepancy (μm)** | 31.6 ± 7.5 | 45.3 ± 8.8 | 68.4 ± 14.5 | <0.001 |
| **Mean angular deviation (degrees)** | 0.18 ± 0.06 | 0.29 ± 0.09 | 0.47 ± 0.14 | <0.001 |

*Precision was calculated as the mean intra-group pairwise deviation after 3D superimposition.*

**Table 3:** Passive-fit gap and distribution of deviation zones

| Outcome | Fully digital (n=10) | Hybrid (n=10) | Conventional (n=10) | p-value |
|---|---|---|---|---|
| **Mean passive-fit gap (μm)** | 24.9 ± 6.2 | 35.8 ± 7.4 | 58.6 ± 13.1 | <0.001 |
| **Maximum passive-fit gap (μm)** | 48.7 ± 10.5 | 67.9 ± 13.2 | 104.6 ± 22.8 | <0.001 |
| **Specimens with gap <50 μm, n (%)** | 9 (90.0) | 7 (70.0) | 3 (30.0) | 0.026 |
| **Surface deviation 50-100 μm (%)** | 14.2 ± 4.9 | 20.7 ± 5.6 | 27.6 ± 7.1 | <0.001 |
| **Surface deviation >100 μm (%)** | 3.4 ± 1.7 | 9.2 ± 3.1 | 17.6 ± 6.3 | <0.001 |

*Passive-fit gap values were obtained using the single-screw test under stereomicroscopic magnification.*

## Discussion:

The present *in vitro* study showed that the fabrication workflow had a significant effect on the trueness and precision of the FAPs. The fully digital workflow exhibited the smallest root mean square deviation, the smallest discrepancy between plants and the most favorable passive-fit values. The hybrid workflow was more successful than the traditional workflow, but was not as accurate as the fully digital workflow. Thus, the null hypothesis was rejected. The overall superior trueness of the fully digital workflow could be attributed to the minimisation of cumulative analog errors. Traditional methods involve impression material handling, coping splinting, stone cast making, resin pattern making, investing, casting and finishing. There can be dimensional change in each step. Digital acquisition and CAD/CAM manufacturing eliminate some of these intermediate steps, enabling the transfer of implant position data into the design and milling environment **[9]**. The results are in line with evidence that complete-arch digital implant scanning can provide good accuracy if the scan bodies are properly positioned, the scanning strategy is standardized and the reference geometry is recorded without interruption. But complete digital accuracy is not guaranteed. When a long edentulous span is present, especially with widely spaced or angulated implants, errors can be compounded in the image stitching process. In the present study, this was avoided by employing a standardized scan path, a calibrated scanner and a repeat operator protocol **[10]**. The accuracy of the hybrid workflow was intermediate. This finding is clinically significant, as full-arch rehabilitation is often performed using hybrid pathways. Many clinics take conventional impressions for initial implant position and then take a digital cast scan and CAD/CAM produce the framework for the definitive prosthesis. The hybrid approach could thus minimize manual framework fabrication errors while maintaining the familiar analog impression techniques. In the current study, the hybrid specimens had lower RMDE and passive fit than the conventional specimens, indicating that digital design and milling played a significant role in the improvement of standardization **[11]**. The conventional workflow had the largest deviation values and the largest variability. This does not mean that traditional techniques are not clinically acceptable, since open-tray impressions are still an accepted technique for full-arch implant cases. Instead, the results indicate that conventional fabrication is more sensitive to procedural factors like splinting technique, removal of the impression, stone expansion, wax pattern distortion, casting shrinkage and finishing. These cumulative errors could be responsible for the greater maximum deviations found in the vicinity of the terminal implant interfaces and cantilever areas **[12]**. The precision results are especially significant as they are a measure of whether a workflow can generate the same prostheses under the same conditions. The fully digital workflow yielded the lowest pairwise deviation, indicating high reproducibility of scanning, design and milling. The hybrid workflow had moderate repeatability and the conventional workflow had greater variability. Even if the average trueness seems satisfactory, in clinical practice, lower precision can lead to further adjustment, verification or remake procedures **[13].** A successful passive fit is still a key factor in full-arch prosthodontics. There is no universal threshold to determine a completely passive prosthesis, but lower vertical gaps are generally desired to minimize mechanical stress at the implant-abutment interface. The fully digital group had the lowest mean passive fit gap, with most specimens having gaps < 50 μm. The conventional group had much larger gaps, particularly in the tests with a single screw at the end. This finding is in favor of the use of 3D superimposition in combination with mechanical seating evaluation, as digital deviation values do not necessarily reflect clinical passivity **[14]**. A color-map analysis was also used to gain further insight into the location of discrepancies. The fully digital workflow exhibited a higher percentage of the surface area within ±50 μm and a more uniform adaptation. Conventional prostheses exhibited a larger deviation in posterior and cantilever regions, however. These areas are especially sensitive as small angular errors in the transfer of the implant can be amplified over long distances. This further emphasizes the importance of evaluating the surface behavior as whole, not just a few linear dimensions **[15]**. The study also emphasizes the need for the standardization of accuracy assessment. Reported deviation values can vary significantly based on the differences in the reference scanners, alignment algorithms, mesh cleaning, scan-body library files and measurement zones. Best-fit alignment can spread error over the surface and can underestimate the misfit in a localized area if poorly controlled. Thus, the same reference model, scanner, design dimensions and superimposition method were used for all groups to minimize methodological bias **[16]**. Clinically, fully digital workflows can enhance efficiency, reproducibility, communication and data archiving. However, they need investment in scanning systems, software literacy, training and laboratory integration. In clinics

where full-arch digital implant scanning is not yet a standard practice, hybrid workflows can be a viable and practical option, especially when transitioning between different workflows. In some cases, conventional workflows are still relevant, but may need to be verified with jigs, correct soldering or welding and repeated clinical evaluation to account for possible cumulative distortion **[17]**. There are some limitations to this study. It was done in a controlled *in vitro* setting without saliva, blood, soft-tissue mobility, restricted mouth opening, patient movement, or intraoral scanning optical challenges. One scanner, one implant system, one reference arch and one prosthesis design were tested. The standard procedure was carried out by an experienced technician and results may vary depending on the operator. Future studies should assess various scanner systems, scan body designs, and implant angulations, edentulous arch forms, manufacturing materials and clinical results including chairside adjustment time, screw complications, prosthesis survival and patient-reported comfort **[18, 19]**.

**Conclusion:**

We show that fully digital workflow achieved the highest trueness and precision for full-arch prosthesis fabrication. The conventional workflow showed the greatest dimensional deviation and the least predictable passive fit. Thus, fully digital workflows should be preferred for full-arch implant prostheses whenever clinically applicable.

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