Development and Validation of a Novel Virtual-Fit Method for Evaluating Intraoral Scanner Accuracy

Ph.D. Thesis Booklet

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1. Introduction

The accuracy of fit between a dental restoration and its abutment teeth is a critical factor influencing the long-term success of tooth-supported prostheses. Intraoral scanners (IOSs) have become an integral part of digital dentistry, offering efficient workflows and seamless integration with CAD/CAM systems. While their accuracy is well established for single-unit and short-span restorations, the reliability of IOSs for complete-arch prostheses remains controversial due to the potential accumulation of scanning errors across long spans.

Most IOS accuracy studies rely on conventional scan-to-scan superimpositions, where penetration between surfaces is allowed. However, this approach may underestimate clinically relevant discrepancies because they do not replicate the physical seating of a restoration. Furthermore, important restorative design parameters, such as cement spacing, are rarely considered despite their significant influence on prosthesis fit.

Therefore, a more clinically relevant method is needed to evaluate IOS accuracy by linking digital scanning errors to actual restoration fit. Such an approach may provide a more realistic assessment of scanner performance and improve the predictability of complete-arch restorations.

2. Objectives

2.1 Application of the virtual-fit method for fixed complete denture cases designed on intraoral scans: Effect of cement spacing – Study 1

Aims of the study were:

1. To validate the virtual-fit alignment algorithm.
2. To investigate the effect of cement spacing on accuracy of intraoral scanner by means of virtual-fit method.
3. To assess the relationship between the virtual-fit method and conventional trueness measurements.

2.2 Complete-arch accuracy of seven intraoral scanners measured by the virtual-fit method – Study 2

Aims of the study were:

1. To compare the complete-arch accuracy (trueness and precision) of seven different intraoral scanners by the virtual-fit method.
2. Comparing the effect of two cement spacings on accuracy across intraoral scanners.

3. Methods

3.1. Application of the virtual-fit method for fixed complete denture cases designed on intraoral scans: Effect of cement spacing – Study 1

3.1.1 Model fabrication and scanning

Four maxillary arch models prepared for fixed complete prostheses were 3D-printed with varying numbers and distributions of abutment teeth (Models A–D). High-precision industrial scans were obtained and used as reference models (ATOS Capsule MV120, Carl Zeiss GOM Metrology GmbH, Germany). Each model was subsequently scanned three times using two intraoral scanners, Emerald S (Planmeca, Finland) and Medit i700 (Medit, South Korea). Scans were coded according to the model and scan replicate.

3.1.2 Scan segmentation

The reference and IOS scans were imported in STL file format into the dental lab CAD/CAM software Exocad (Exocad DentalDB, Exocad GmbH, Germany). In Exocad, the tooth abutments were digitally segmented from the model.

3.1.3 Framework design

Three complete-arch tooth-supported fixed prosthesis frameworks were designed in Exocad based on IOS datasets from two scanners, four models, and three scan repetitions (n=72), using three different cement space settings. A common insertion axis was defined for all abutments. The marginal ramp

was set at 250µm for all designs. Cement space and additional spacing functions were used.
Three cement space configurations were tested:

- group 70 (70µm cement gap without additional spacing)
- group 70+20 (70µm cement gap with 20µm additional spacing, resulting in 20µm at the marginal ramp and 90µm internally)
- group 140 (140µm cement gap without additional spacing).

All frameworks were exported as STL files and defined as "bottom designs," representing only the intaglio (internal and marginal) surfaces of the restorations.

3.1.4 Measurements

After establishing the bottom designs, STL files were imported into Zeiss Inspect 2022 (Carl Zeiss GOM GmbH, Braunschweig, Germany) metrology software for alignments and surface comparisons. Four different types of gap measurements were performed based on mesh type, cement space setting, and comparison area:

- original (Exocad) position
- outside-IOS alignment
- outside-reference alignment
- conventional scan-to-scan alignment

For all four alignment methods, MAD between the aligned surfaces was calculated in two areas: internal gap area (abutments excluding a 250µm marginal ramp) and marginal gap area (inverted selection).

3.1.5 *Statistical analysis*

Descriptive statistics are reported as median, first (Q1), and third (Q3) quartiles. With an n=12 sample size per group (four models times three repeats), accuracy for both IOSs was evaluated using the virtual-fit method. Gaps were calculated by subtracting outside-IOS gaps from outside-reference gaps to eliminate alignment errors and cement spacing unevenness, using a 100μm threshold to identify inferior scans.

The Mann–Whitney U test compared the MAD of the two IOSs, while Friedman's ANOVA analyzed differences between spacing groups, with significance values adjusted via Bonferroni correction. Spearman's Rho evaluated the correlation between the outside-reference and scan-to-scan methods, and the Wilcoxon Signed-Rank test compared their medians. The significance threshold was set at $p<0.05$. All analyses were performed using IBM SPSS (v28).

3.2. Complete-arch accuracy of seven intraoral scanners measured by the virtual-fit method – Study 2

3.2.1 Model fabrication and scanning

3D-printed resin maxillary arches from subsection 3.1.1 were utilized. For creating reference models each dental model was scanned with the same industrial scanner (ATOS Q MV100, Zeiss Inspect software v2023.2).

Each model was then scanned three times by seven intraoral scanners (n=12 per IOS):

- Aoralscan 3 (Shining3D, Hangzhou, China)
- Emerald S (Planmeca, Helsinki, Finland)
- Helios 600 (Eighteeth, Changzhou, China)

- Lumina (iTero Align Technology, Tempe, USA)
- Medit i700 (Medit, Soul, South Korea)
- Primescan (Dentsply Sirona, Charlotte, USA)
- Trios 5 (3Shape, Copenhagen, Denmark).

3.2.2 Scan segmentation

The reference and IOS scans were imported, and the tooth abutments were digitally segmented in Exocad software following the exact protocol described in subsection 3.1.2.

3.2.3 Framework design

Two complete-arch tooth-supported fixed prosthesis frameworks with different cement spacings on each IOS scan (seven IOSs, four models, three repeats, two cement gaps, n=168) were designed. Insertion axis, pontics, and CAD methods followed the previous study, with the same marginal ramp. Two spacing groups were compared:

- **group 70:** 70µm cement gap, 0µm additional spacing
- **group 70+20:** 70µm cement gap, 20µm additional spacing (20µm gap marginally, 90µm internally).

Exported designs included only the intaglio surface of the crown abutments.

3.2.4 Measurements

CAD designs and reference scans were imported into Zeiss Inspect software. Surfaces were pre-aligned with iterative closest point (ICP) algorithm, followed by an outside alignment algorithm to simulate a clinical try-in. This virtual-fit method isolates IOS inaccuracy by eliminating physical fabrication errors.

The mean distance between aligned surfaces was calculated for two regions:

- **internal cement gap:** Measured across the abutments, excluding the 250µm marginal ramp.
- **marginal cement gap:** Measured within a 100µm zone from the finish line.

3.2.6 Statistical analysis

Statistical analyses were performed using IBM SPSS (v28). As the data violated normal distribution assumptions, the Kruskal-Wallis test was used to compare the median gaps of the IOSs and categorize them into homogeneous subsets. The Wilcoxon signed-rank test compared median gaps between the cement spacing groups.

Precision (reproducibility) was evaluated via mean absolute error (MAE), calculated as the absolute difference between individual gap values and their group mean. IOS MAE values were compared using the Kruskal-Wallis test for homogeneous subsets, while the Wilcoxon test compared MAE between the cement spacing groups.

4. Results

4.1 Application of the virtual-fit method for fixed complete denture cases designed on intraoral scans: Effect of cement spacing – Study 1

4.1.1 Validation of gap measurement

First, the gap measurement was validated by comparing it to the set cement spacing values in the original position of the bottom design on the model. The measured gap was significantly higher in all groups than the set cement space, but the difference ranged only between 0.2–1.7 μm at the internal surface and 3.7–9.9 μm at the margin.

4.1.2 Validation of the virtual-fit method

The virtual-fit method was validated by comparing the measured gap after outside alignment of the intaglio design with the IOS scan (used for the design) against the gap in its original position. In Groups 70 and 140, the outside-aligned gap was significantly larger than both the set cement space and the original position gap. Conversely, in Group 70+20, both internal and marginal gaps were significantly smaller than in the original position. The 20μm additional spacing allowed the design caps to seat closer to the abutment.

4.1.3 Accuracy of intraoral scanners

Internal error (outside-IOS minus outside-reference) was similar across spacing groups but consistently higher for Medit i700 than Emerald S. Emerald S showed no internal errors >100 μm, while Medit i700 had one outlier that decreased with adjusted spacing.

For marginal gaps, Medit i700 showed significantly higher values and multiple exceedances of 100µm, including large outliers, whereas Emerald S remained below 100µm in all cases. The scan-to-scan ICP method showed similar trends but missed outliers. It correlated with the virtual-fit method, though it underestimated errors (internal gap: 2.6–2.8×higher, marginal gap: 4.0–4.5×higher).

4.2 Complete-arch accuracy of seven intraoral scanners measured by the virtual-fit method - Study 2

4.2.1 Median marginal gap (trueness)

Median marginal gaps differed significantly between IOSs in both cement spacing groups. In group 70, Medit i700, Primescan, and Emerald S showed the lowest values, followed by Lumina, Aoralscan 3, and Trios 5, while Helios 600 had the highest gap. Increasing cement spacing (70 to 70+20) significantly reduced gaps for Lumina and Aoralscan 3, slightly improving their ranking and making them comparable to Primescan and Emerald S in group 70+20.

4.2.2 Median internal gap (trueness)

Median internal gaps differed significantly between IOSs in both spacing groups. In group 70, Medit i700, Primescan, and Emerald S showed the lowest values, followed by Aoralscan 3, with Trios 5 and Lumina forming higher subsets; Helios 600 showed the highest gaps. Increasing cement space (70 to 70+20) slightly increased internal gaps for all IOSs except Lumina, causing partial merging of the middle subsets while maintaining the overall ranking.

4.2.3 Mean absolute error (precision) of the marginal gap

Marginal gaps were <100µm for Medit i700, Primescan, Emerald S, and Trios 5 in both spacing groups. Exceedances occurred in Lumina, Aoralscan, and increased in Helios 600 from group 70 to 70+20.

MAE differed significantly between IOSs in both groups: in group 70, Medit i700, Trios 5, and Emerald S showed the lowest values, followed by Primescan, with higher values for Lumina, Helios 600, and Aoralscan 3. Variability decreased for Emerald S and Aoralscan 3 in group 70+20, with overall similar ranking but more overlap between groups.

4.2.4 Mean absolute error (precision) of the internal gap

The median MAE was significantly different between IOSs in both cement spacing groups. In group 70, the MAE in Medit i700, the Trios 5, and Emerald S were in the first-best homogenous subset, followed by Primescan and Lumina. Helios 600 was in the third subset, and Aoralscan 3 was in the fourth subset. The variability of Aoralscan 3 decreased significantly by additional cement spacing (group 70+20). In group 70+20, the ranking was similar but with more overlaps between the subsets.

5. Conclusions

- The virtual-fit method reliably simulates the intended cement space configuration while preventing surface interpenetration during ICP alignment.
- Cement spacing significantly affected internal and marginal adaptation.
- The virtual-fit method was able to identify clinically relevant discrepancies and suboptimal scans that remained undetected using conventional scan-to-scan trueness analyses.

- The findings (trueness and precision) demonstrated statistically significant differences among the seven different intraoral scanners.
- Cement spacing significantly influenced restoration fit across scanners.

6. Bibliography of the candidate's publications

Publications directly related to the thesis:

Borbola D, Mikolicz A, Romanszky L, Sersli G, DeFee M, Renne W, Vag J. *Complete-arch accuracy of seven intraoral scanners measured by the virtual-fit method.* Journal of Dentistry, 2024 Oct;149:105281.
Impact factor: 5,5 (ranking: D1)

Vag J, Romanszky L, Sersli G, DeFee M, Renne W, Mangano F, **Borbola D**. *Application of the virtual-fit method for fixed complete denture cases designed on intraoral scans: Effect of cement spacing*. Journal of Dentistry, 2024 Feb;141:104780.
Impact factor: 5,5 (ranking: D1)

Publications indirectly related to the thesis:

DeFee M, Renne W, Shazib MA, Queiroz A, Mennito A, **Borbola D**, Vag J. *Virtual-fit assessment of full-arch implant photogrammetry accuracy in a human cadaver model.* Journal of Dentistry, 2026 Jul;170:106668.
Impact factor: 5,8 (ranking: D1)

Borbola D, Vag J. *Unifying intraoral scanner, computer-aided manufacturing, and final crown accuracy: A virtual-fit method for marginal gap evaluation.* Journal of Dentistry, 2025 Dec;163:106113.
Impact factor: 5,8 (ranking: D1)

Borbola D, Berkei G, Simon B, Romanszky L, Sersli G, DeFee M, Renne W, Mangano F, Vag J. *In vitro comparison of five desktop scanners and an industrial scanner in the evaluation of an intraoral scanner accuracy*. Journal of Dentistry, 2023 Feb;129:104391.
Impact factor: 4,8 (ranking: D1)

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