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Agreement of digital and conventional impression techniques for subgingival finish line reproduction: A clinical pilot study

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Abstract

Background

The reproduction of subgingival finish lines is critical for the success of fixed prosthodontic restorations. However, the reliability of digital impression techniques for the reproduction of subgingival margins is still questionable. This study evaluated the inter-technique agreement and reliability of conventional (CIT) and digital (DIT) impression techniques for capturing subgingival finish lines (SGFLs).

Methods

Twenty first molars indicated for all-ceramic crowns were prepared with 1-mm shoulder finish lines placed 0.5–1 mm subgingivally. Following standardized gingival retraction, four impression techniques were compared: **IOS** – intraoral scanning (CEREC Omnicam, Sirona); **IMS** – digital models obtained from polyvinyl siloxane (PVS) impressions scanned with Medit T500; **DIS** – scanned type IV stone casts (3Shape D2000); and **CIM (Control)** – master casts digitized using ATOS Compact Scan (Carl Zeiss). SGFL was measured at the midpoint of the buccal, mesial, distal, and lingual surfaces after virtual model superimposition (GOM Inspect 2018). Inter-technique agreement was assessed using intraclass correlation coefficients, and Bland–Altman (BA) analysis evaluated bias and variability.

Results

CIM showed excellent reliability across all surfaces (ICC > 0.90). **Buccal surface**: IOS showed moderate reliability (ICC = 0.704), while IMS (0.917) and DIS (0.914) were excellent. **Proximal surfaces** varied: mesial ICCs were good for IMS (0.824) and excellent for DIS (0.931) but poor for IOS (0.526); distal ICCs were good for IMS (0.707) and DIS (0.837) but poor for IOS (0.353). **Lingual surface** exhibited poor agreement for all DITs (IOS = 0.298; IMS = 0.439; DIS = 0.428).

Conclusion

CIM provided the most reliable capture of SGFLs. IMS and DIS exhibited acceptable agreement for buccal and proximal margins but performed poorly on lingual surfaces. IOS demonstrated poor reliability beyond the buccal region. These findings suggest that conventional workflows remain an important reference method for subgingival finish line reproduction.

Trial registration:

Not applicable.

1 Background

The rehabilitation of severely compromised dentition using single crowns and fixed partial dentures has long been the gold standard in restorative dentistry, accounting for over 60% of all restorative procedures.[1,2] The clinical success and longevity of these prostheses are critically dependent on the accuracy of the definitive impression, particularly the precise reproduction of finish line of tooth preparation, as discrepancies can compromise fit and function.[3–6,7] Inaccurate or incomplete capture of the finish line can compromise marginal integrity, increase the risk of restoration fracture, and contribute to biological complications.[7,8] Although DITs have gained popularity due to enhanced efficiency and patient comfort, their reliability in accurately capturing SGFLs remains uncertain.[2] While several studies have assessed the marginal gaps of definitive restorations, relatively few have addressed the foundational step of finish line capture accuracy, an essential determinant of all subsequent prosthetic outcomes.

The CIT, using elastomeric impression materials, is the most popular method for recording intraoral anatomy and sending this information to the dental laboratory.[3,9] Several studies have been conducted on the accuracy and dimensional stability of elastomeric impression materials.[10–13] PVS are said to be most accurate in terms of surface replication and dimensional stability.[14,15] The emergence of digital dentistry has revolutionized contemporary dental practice, with digital impression technology being developed to address the technique sensitivity and potential for human error inherent in CIT.[16,17] DIT offers numerous clinical advantages, including improved cost-efficiency, reduced chair side time, enhanced three-dimensional visualization of tooth preparations and occlusion, and more accurate evaluation of interocclusal space during prosthesis design.[18] Furthermore, digital datasets can be electronically archived and transmitted without compromising data integrity, facilitating seamless communication between clinicians and dental laboratories.[19]

Extensive comparative studies have evaluated various parameters, including accuracy, patient acceptance, operator preference, and time efficiency, between digital and conventional impression methods.[3,19–22] The literature consistently demonstrates superior patient acceptance and operator satisfaction with digital workflows.[3] Accuracy assessments have employed multiple evaluation criteria, including precision of impressions, internal and marginal fit of restorations, and superimposition of virtual image of impression and die.[9,19–24] While several investigations report that digital systems can achieve accuracy comparable to or exceeding conventional methods [3,4,25,26], it is noteworthy that the majority of these studies have focused on supragingival applications, leaving a significant gap in our understanding of digital impression performance for subgingival margin reproduction. Improper capture of finish lines lead to marginal discrepancies of restorations and expose luting cements to the oral environment, potentially leading to dissolution, microleakage, plaque accumulation, secondary caries, and eventual restorative failure.[27–29] While supragingival margin placement is ideal, various clinical

situations such as short clinical crowns, aesthetic demands, and extensive caries frequently necessitate SGFL placement.[30]

Subgingival margin capture presents unique technical challenges requiring effective soft tissue displacement, hemorrhage control, and moisture management.[2,31,32] CITs have historically addressed these requirements through gingival retraction cords and careful injection of light-body impression material into the sulcus.[31] Conventional impressions using PVS materials have demonstrated superior accuracy in subgingival environments due to their ability to displace tissues and fluids and replicate undercuts.[33] In contrast, digital impression systems rely on optical principles requiring moisture-free environments and unobstructed visibility for accurate data acquisition.[2] Intra oral scanners struggle with subgingival moisture and access, with scanner accuracy declining significantly as depth increases.[34] Despite their fundamentally different approaches, neither conventional nor digital impression techniques have been sufficiently validated for subgingival margin reproduction.

Cagidiaco et al.[2] demonstrated that margin location significantly impacts scanning accuracy, cautioning against deep subgingival preparations for intraoral scans. Recent clinical trials confirm that intra oral scanner accuracy deteriorates markedly with deeper subgingival margins, necessitating modified protocols for such cases.[35] Conversely, Nedelcu et al.[36] reported that certain intraoral scanners could achieve superior finish line accuracy compared to conventional methods under controlled in vitro conditions. However, the in vitro models inherently lack clinical variables that critically affect subgingival margin capture: gingival crevicular fluid, hemorrhage, and dynamic tissue displacement during retraction.

This clinical agreement study addressed the research question: Can DITs achieve comparable reliability (agreement) to CITs in recording SGFLs across all tooth surfaces in clinical settings? The primary objective was to compare the inter-method agreement of three DITs (intraoral scanning, impression scanning, and die scanning) with CITs in capturing SGFLs, using ICC and BA analysis. A secondary objective was to evaluate surface-specific variations (buccal, mesial, lingual, distal) to identify clinical scenarios where digital workflows could substitute conventional methods. The null hypothesis stated that no significant difference in inter-method agreement exists between CITs and DITs for SGFL reproduction across all surfaces.

2 Methods

This single-centre, within-subject, cross-sectional clinical pilot study compared the agreement of intraoral scanning, impression scanning, and die scanning against conventional PVS impressions for reproducing 1-mm SGFLs. The study protocol was approved by the Ethics Committee of Amrita School of Medicine, Kochi (Ref. ECASM-AIMS-2022-179) and was conducted in accordance with the Declaration of Helsinki and its subsequent amendments

Clinical Setting

A sample size of 20 participants was deemed appropriate for this pilot feasibility study, in line with recommendations that 12–30 participants are sufficient to estimate parameters such as recruitment rates, retention, and data variability for planning a larger trial.[37] This sample size allows for the identification of key logistical and practical issues without overcommitting resources at this exploratory stage. Twenty participants (10 male, 10 female; aged 18–40 years) were recruited through convenience sampling. To minimize biological variability, only patients with thick gingival biotypes were included. Gingival thickness was assessed via transgingival probing, and biotype classification was confirmed by the absence of periodontal probe translucency. Thick biotypes were selected due to their predictable soft tissue response to displacement, reduced susceptibility to trauma-induced rebound, and lower risk of post-procedural gingival recession.[38,39] All participants provided written informed consent, required all-ceramic crowns on first molars, and had healthy periodontal conditions without gingival recession. Recruitment of patients and workflow are shown in Fig. 1.

Tooth Preparation, Gingival Retraction and Making of Impressions.

To minimize biological width violation, all tooth preparations were performed with the finish line placed 0.5–1.0 mm subgingivally, a clinically safe margin depth.[38] A single experienced prosthodontist prepared maxillary and mandibular first molars using standardized CAD/CAM protocols, maintaining a 1-mm-wide shoulder design.[37,40,41] Preparations were completed using coarse- and fine-grit tapered diamond burs (#101, #SF101, Shofu Dental India Pvt. Ltd., India) to ensure uniform margins. A gingival marginal trimmer (MT28H#3, GDC Fine Crafted Dental Pvt. Ltd., India) was used to mark midpoint references on each axial surface, which were extended to the SGFL to aid digital superimposition. Midpoints were selected due to minimal tissue interference, optimal visibility, maximum accessibility, and ease of preparation. Following tooth preparation, gingival displacement was achieved using a double-cord technique (#00 followed by #1, Ultrapak, Ultradent, USA) soaked in an astringent solution (Waldent Hemostatic Liquid, Waldent Innovations Pvt. Ltd., India) to enhance tissue displacement.[2,42] For intra oral scanning, the #1 cord was removed while the #00 cord remained in situ.[2,43,44] The sulcus was rinsed for 10 seconds with water spray and gently air-dried to eliminate hemostatic interference.[45] Intraoral scans were acquired using the CEREC Omnicam system (Sirona, Germany), following the manufacturer's protocol. Scan data were processed using CEREC software (v5.2.9, Sirona), quality-checked, and exported as standard tessellation language (STL) files. These scans, completed within 5 minutes per arch, comprised Group IOS for comparative analysis.

Immediately following intraoral scanning, definitive impressions were made using a double-step PVS putty-wash technique (GC Flexceed, GC India Dental Pvt Ltd, India). All impressions were visually inspected under 2.5× magnification (Eisco Magnifier Glass, Eisco, India) for surface defects, disinfected by immersion in 2% glutaraldehyde solution (Gigasept GTA, Schulke India Pvt. Ltd., India) for 10 minutes, rinsed with distilled water, air-dried, and scanned using a laboratory impression scanner (Medit T500, Medit Corp., Seoul, South Korea) with a manufacturer-reported accuracy of 7 μm.[46] The scan data were processed using dedicated software (colLab v2.0.0.4, Medit Corp.) and exported as STL files, which

comprised Group IMS for comparative analysis. The PVS impressions were poured using Type IV dental stone (Fuji Rock EP, GC India Dental Pvt. Ltd., India) following the manufacturer's recommended water-to-powder ratio and mixing protocol. After complete setting, the definitive casts were carefully retrieved and examined under 2.5× magnification (Eisco Magnifier Glass, Eisco, India) to detect voids or surface irregularities. Dies were prepared from defect-free casts using a laser die-cutting system and scanned using a high-resolution laboratory die scanner (D2000, 3Shape A/S, Denmark) with a manufacturer-reported accuracy of 5 μm.[47] To ensure procedural consistency, all laboratory scanning procedures for both Group IMS and Group DIS were performed by a single dental technician under standardized conditions.

Generation of Reference Virtual Models

The master casts were digitized using an industrial-grade optical scanner (ATOS Compact Scan 170 FOV, Carl Zeiss GOM Meteorology, GmbH, Germany) with verified volumetric accuracy of ± 9 μm (ISO 10360-8 compliant), establishing the control group (Group CIM) [48]. This system was selected as the reference standard based on its traceable metrological calibration, comprehensive surface capture capability, and documented reliability in dental research applications [49]. While both the laboratory scanners (D2000, 3Shape A/S; T500, Medit Corp.) demonstrated marginally higher nominal point accuracy, the ATOS system exhibited superior overall volumetric precision. This enhanced spatial consistency enabled reliable detection of sub-10 μm marginal discrepancies and ensured accurate three-dimensional superimposition of STL datasets across all experimental groups (IOS, IMS, DIS).

Superimposition of Reference and Test Images

All datasets were aligned using metrology software (GOM Inspect 2018, Carl Zeiss GOM Metrology, GmbH, Germany), with the ATOS-derived reference model as the spatial framework, after systematically excluding extraneous scan data beyond the region of interest to optimize superimposition accuracy (Fig. 2a, Fig. 2b, Fig. 2c, Fig. 2d). The SGFL width was measured at mid-buccal, mid-lingual, mid-mesial, and mid-distal locations.

Statistical Analysis

Descriptive statistics (mean ± standard deviation [SD]) were calculated for each group using IBM SPSS Statistics (v20.0; IBM Corp., Armonk, NY, USA). The reliability of SGF measurements obtained from the CIT and DIT was evaluated using a two-way mixed-effects intraclass correlation coefficient (ICC) with absolute agreement.[50] ICC values were interpreted as follows: poor (< 0.50), moderate (0.50–0.75), good (0.75–0.90), or excellent (> 0.90) reliability. Statistical significance was set at $p < 0.05$. Bland-Altman analysis was performed to assess agreement between methods, with bias (mean difference) and 95% limits of agreement (LoA: ±1.96 × SD of differences) plotted graphically. All analyses were conducted at a 95% confidence level.

3 Results

The study evaluated the reliability and agreement between CIM (two stage putty-wash impression) and DIT (intraoral scanning, impression scanning, and die scanning) for capturing SGFL margins across buccal, mesial, lingual, and distal surfaces. The mean SGFL width for the buccal surface was 1.17 ± 0.229 mm for CIM, compared to 0.781 ± 0.277 mm for IOS, 1.014 ± 0.254 mm for IMS, and 1.053 ± 0.255 mm for DIS. ICC analysis revealed moderate agreement between IOS and CIM (ICC = 0.704), while IMS (ICC = 0.917) and DIS (ICC = 0.914) demonstrated excellent agreement. For the mesial surface, the mean SGFL width was 0.969 ± 0.267 mm for CIM, 0.647 ± 0.179 mm for IOS, 0.814 ± 0.199 mm for IMS, and 0.887 ± 0.251 mm for DIS. IOS exhibited poor reliability (ICC = 0.526, 95% CI: -0.196–0.813, p = 0.056), whereas IMS showed good agreement (ICC = 0.824, 95% CI: 0.556–0.930, p < 0.001), and DIS achieved excellent reliability (ICC = 0.931, 95% CI: 0.826–0.973, p < 0.001). On the lingual surface, the mean SGFL width was 0.918 ± 0.202 mm for CIM, compared to 0.739 ± 0.219 mm for IOS, 0.804 ± 0.220 mm for IMS, and 0.880 ± 0.266 mm for DIS. All digital techniques performed poorly, with ICC values indicating weak agreement (IOS: ICC = 0.298, 95% CI: -0.775–0.565, p = 0.224; IMS: ICC = 0.439, 95% CI: -0.418–0.778, p = 0.109; DIS: ICC = 0.428, 95% CI: -0.446–0.774, p = 0.116). The negative lower bounds of the 95% confidence intervals suggested instances where measurement disagreement exceeded agreement. For the distal surface, the mean SGFL width was 0.986 ± 0.264 mm for CIM, 0.713 ± 0.202 mm for IOS, 0.833 ± 0.268 mm for IMS, and 0.896 ± 0.279 mm for DIS. IOS showed poor reliability (ICC = 0.353, 95% CI: -0.634–0.744, p = 0.175), while IMS (ICC = 0.707, 95% CI: 0.259–0.884, p = 0.005) and DIS (ICC = 0.837, 95% CI: 0.588–0.935, p < 0.001) demonstrated good to moderate agreement.

CIM consistently demonstrated the highest reliability across all surfaces. Digital methods, namely IMS and DIS, provided clinically moderate to excellent reliability for buccal and proximal margins but performed poorly on lingual surfaces (Table 1). Figure 3 shows the comparison of mean SGFL widths (mm) at buccal, lingual, mesial, and distal aspects between CIM, IOS, IMS and DIS. IOS exhibited limited reliability beyond the buccal region, underscoring the need for hybrid techniques in complex anatomical scenarios. IMS and DIS achieved excellent buccal and good-to-excellent proximal reliability, intraoral scanning showed only moderate buccal reliability and poor performance on other surfaces. Critically, all digital methods showed poor reliability for lingual SGFL margin reproduction. Bland-Altman plots (Fig. 4a, Fig. 4b, Fig. 4c) assessed bias and variability between CIM and digital techniques. The narrowest limits of agreement were observed for IMS and DIS on buccal and mesial surfaces, indicating better consistency. IOS exhibited wider variability, particularly on lingual and distal surfaces, reinforcing its limitations in anatomically challenging regions. Dashed lines represent limits of agreement (±1.96 SD).

4 Discussion

This surface-specific analysis rejects the null hypothesis and demonstrates significant inter-method variability in the reliability of reproducing SGFLs between DIT and CIT. CIM consistently outperformed digital methods across all surfaces, particularly for lingual and proximal margins where current digital workflows showed critical limitations. The observed reliability between techniques followed a clear hierarchy, with CIM showing superior performance, followed by DIS, IMS, and IOS.

The CIM group, serving as the reference standard, demonstrated superior performance to capture subgingival detail, was measured using industrial scanner (±9 µm accuracy). The superior performance of CIT in our study aligns with the well-established literature demonstrating their accuracy in surface replication and dimensional stability.[10-15] The conventional elastomeric materials demonstrate superior performance in subgingival scenarios due to their favorable rheological properties, which facilitate effective flow into the gingival sulcus.[51] The two-step impression technique further enhances accuracy, as the heavy-body material displaces gingival tissue apically and, ensuring complete capture of the SGFLs and adjacent tooth structure.[52,53] Several studies have shown that CIT tend to achieve greater precision in these challenging subgingival scenarios.[2,36,54, 55]

The demonstrated superiority of PVS impressions in reproducing subgingival margins must be interpreted within the context of gingival biotype. This study specifically included patients with thick biotypes, due to their well-documented clinical advantages.[56,57] As thick biotypes allow more predictable tissue displacement during retraction and exhibit greater resistance to rebound, both of which are critical for accurate finish line registration.[58] While this selective inclusion strengthens the internal validity of our comparison between conventional and digital methods, it necessarily limits the generalizability of findings to thin biotypes, which were excluded owing to their greater susceptibility to procedural trauma and variability in tissue response.[56,59] This methodological choice likely created optimal conditions for CIM to perform at their best and should be considered when extrapolating results to broader clinical scenarios. However, conventional techniques are not without limitations, including potential dimensional instability from polymerization shrinkage and technique sensitivity during material handling.[60,61,62] These factors, while not eliminating the superiority of PVS for subgingival margin capture, do highlight areas where digital methods could potentially offer advantages with further development. In a review by Donovan and Chee similarly concluded that while PVS remains the gold standard, its technique sensitivity warrants continued investigation of alternative methods.[63]

The poor performance of intraoral scanning on lingual and distal surfaces is attributed to both anatomical and technological factors. Undercuts and soft tissue interference, especially from the tongue, hinder visibility and scanner access on the lingual side, often compromising the digital capture of margins.[54,64] The scanning protocol, soft tissue mobility, and optical challenges such as shadowing and light reflection from adjacent structures, enamel translucency and edentulous span length can also affect scan quality. Abrupt subgingival transitions may be misinterpreted by IOS algorithms, leading to variability in margin width detection.[2,34,54,57] Chiu et al.[65] assessed the impact of scanning resolution on the accuracy of the 3Shape TRIOS 3 intraoral scanner for crown margins and found that marginal discrepancies did not significantly differ between settings, suggesting tooth anatomy impacts accuracy more than resolution settings. This aligns with previous reports by Ferrari Cagidiaco et al. and An et al., who similarly found intra oral scanning struggle with subgingival margin reproduction.[2,31] The findings of the present study agree with the previous studies that subgingival margins were less accurately reproduced with digital scans.[2,37-41,54,57,64,66]

Our study demonstrates a progressive reduction in recorded SGFL width (CIM > DIS > IMS), revealing that each digitalization step inherently compromises detail capture - even under standardized extraoral conditions - independent of intraoral variables. While DIS and IMS showed acceptable reliability in proximal areas, both techniques exhibited inadequate performance for lingual margin reproduction, suggesting fundamental limitations in current digital methods. The noticed variability in DIS group could be due to commercial die scanner resolution limits compounded by microsurface irregularities and reduced light reflectivity.[67-69] The IMS group exhibits further reduction attributed to PVS surface texture causing light scattering, anatomical shadowing beyond scanner dynamic range, and software interpolation artifacts in subgingival zones.[69]

Accuracy assessment in impression techniques has traditionally involved multiple parameters, including impression precision, internal and marginal fit of restorations, and virtual superimposition of scans. Our study innovatively employed direct dimensional measurements of the impressions themselves, circumventing potential artifacts introduced by subsequent crown fabrication processes such as material shrinkage, die spacer application, and technical handling errors inherent in indirect assessment methods.[3,70] While this approach introduces some tooth preparation variability, it better reflects clinical reality, where perfect standardization is unattainable. To mitigate potential confounding effects, we implemented a standardized measurement protocol using precise midpoint reference marks and identical measurement locations across all groups through high-resolution digital superimposition. Midpoints were intentionally selected for their optimal visibility and minimal interference from soft tissues, thereby reducing alignment errors and enhancing measurement reliability. To overcome the limitations of DIT, hybrid protocols combining conventional and digital methods have been explored. Mandelli et al. proposed substituting inadequate digital scans with digitized polyether impressions within CAD software workflows, thereby improving the fidelity of margin reproduction.[50] Similarly, Mangano et al. demonstrated that combining intraoral scanning with 3D-printed trays and PVS impressions for zirconia crowns achieved excellent marginal fits and proximal contacts with minimal occlusal adjustment.[71] These hybrid strategies are promising but require further validation across diverse clinical scenarios and restoration types.

The findings of this study provide critical evidence-based guidance for clinicians managing subgingival margins in restorative dentistry (Table 2). While digital workflows offer advantages in procedural efficiency and patient comfort, our results demonstrate that conventional PVS impressions remain indispensable for achieving optimal accuracy, particularly for linguo-proximal surfaces where current digital methods show significant limitations. The established accuracy hierarchy (CIM > DIS > IMS > IOS) suggests that DIS/IMS may serve as viable alternatives for accessible buccal and proximal margins. These recommendations are particularly relevant for complex cases involving deep margin placements or anatomically challenging areas, where the predictable tissue displacement and detail capture of PVS materials outweigh the convenience of digital approaches.[10-12] Clinicians should therefore adopt a selective, case-specific strategy when choosing impression protocols, prioritizing conventional methods

for critical subgingival margins while considering hybrid techniques that combine digital efficiency with conventional accuracy for appropriate clinical situations.[72]

There are a few limitations which has to be acknowledged in interpreting these results. The CEREC Omnicam, used in this study, is an earlier generation intraoral scanner. Therefore, these results should not be generalized to all current intraoral scanning systems. The results reflect mainly the performance of the analyzed scanner in clinical practice. Further studies should be performed with newer generation scanners with current image acquisition technologies. The study's exclusive focus on marginal width measurement does not address other critical aspects such as marginal shape, continuity, and three-dimensional spatial accuracy. We selected subgingival finish line width as our primary metric because it provides a quantitative, clinically relevant measure of scanning accuracy that directly impacts restoration fit. While we recognize the value of assessing other margin characteristics (shape, continuity, sharpness), these parameters currently lack standardized measurement protocols for subgingival environments. Additionally, the single-center design, modest sample size, usage of one scanner system per technology and lack of analysis on the hardware may affect the generalizability of the results. These limitations mirror those identified in similar studies by Amornvit et al.[17] and Mangano et al.[71], who emphasized the need for multi-center validation with larger sample sizes.

5 Conclusions

Within the limitations of this clinical pilot study, the evaluated digital workflows demonstrated lower agreement than the conventional workflow. While digitized conventional workflows—such as impression and die scanning—showed acceptable agreement for buccal and proximal margins, none of the digital approaches were reliable for lingual margin reproduction. These findings indicate that current digital technologies may not yet be reliable substitutes for conventional impressions in subgingival scenarios. Clinicians should therefore exercise caution when relying solely on intraoral scanning for deep margin capture and may consider hybrid protocols in anatomically challenging regions. As a pilot study, the findings should be interpreted as exploratory and hypothesis-generating. Future advancements should focus on: (i) multicenter validation of IOS systems, (ii) innovative retraction technologies, and (iii) scanner hardware/software improvements (narrower tips, AI reconstruction). Until such advancements become clinically validated, conventional impression techniques remain the most dependable option for precise subgingival margin reproduction.

Abbreviations

BA: Bland–Altman

CIM: Control Impression Model (Reference cast digitized using industrial scanner)

CIT: Conventional Impression Technique

DIS: Die Scanning

DIT: Digital Impression Technique

ICC: Intraclass Correlation Coefficient

IMS: Impression Scanning

IOS: Intraoral Scanning

LoA: Limits of Agreement

PVS: Polyvinyl Siloxane

SD: Standard Deviation

SGFL: Subgingival Finish Line

Declarations

Ethics approval and consent to participate

The study protocol was approved by the Ethics Committee of Amrita School of Medicine, Kochi (Ref. ECASM-AIMS-2022-179) and was conducted in accordance with the Declaration of Helsinki and its subsequent amendments. Written informed consent was obtained from all participants prior to inclusion in the study.

Consent for publication

Not applicable.

Availability of data and materials

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

G.M. contributed to the investigation, data curation, validation, software application, acquisition of funding, and preparation of the original manuscript draft. J.J.L. conceived and designed the study, developed the methodology, conducted the investigation, supervised the project, administered the research, contributed to visualization and validation, and participated in drafting, reviewing, and editing

the manuscript. N.K. performed the statistical analysis and contributed to manuscript preparation. V.K. critically reviewed and revised the manuscript. D.S.S. critically reviewed and revised the manuscript. All authors read and approved the final manuscript.

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Authors' information (optional)

The authors used AI software solely for language refinement, paraphrasing, and grammar correction in this manuscript. No AI tool was used to generate content, draft the manuscript, analyze data, interpret results, or support scientific conclusions. All study design, data interpretation, and conclusions are the authors' original work. The authors take full responsibility for the manuscript's content and integrity.

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Tables

Table 1. Intraclass correlation coefficients (ICCs) comparing conventional (CIM) and digital impression techniques (IOS, IMS, DIS) for SGFL reproduction across tooth surfaces.

Surface	Group	Mean ± SD(mm)	ICC (95% CI)	*p-value**	Reliability
Buccal	IOS	0.781 ± 0.277	0.704 (0.253-0.883)	*0.005*	Moderate
	IMS	1.014 ± 0.254	0.917 (0.790-0.967)	*<0.001*	Excellent
	DIS	1.053 ± 0.255	0.914 (0.782-0.966)	*<0.001*	Excellent
Mesial	IOS	0.647 ± 0.179	0.526 (-0.197-0.813)	*0.056*	Poor
	IMS	0.814 ± 0.199	0.824 (0.556-0.930)	*<0.001*	Good
	DIS	0.887 ± 0.251	0.931 (0.826-0.973)	*<0.001*	Excellent
Lingual	IOS	0.739 ± 0.219	0.298 (-0.775-0.565)	*0.224*	Poor
	IMS	0.804 ± 0.220	0.439 (-0.418-0.778)	*0.109*	Poor
	DIS	0.880 ± 0.266	0.428 (-0.446-0.774)	*0.116*	Poor
Distal	IOS	0.713 ± 0.202	0.353 (-0.634-0.744)	*0.175*	Poor
	IMS	0.833 ± 0.268	0.707 (0.259-0.884)	*0.005*	Good
	DIS	0.896 ± 0.279	0.837 (0.588-0.935)	*<0.001*	Good

*ICC, Intra Class Correlation; SD, Standard Deviation; *Significant at P*<.05.

Table 2. Evidence-based clinical recommendations for subgingival margin reproduction techniques, stratified by tooth surface.

Surface	Recommended Technique	Clinical Considerations
Buccal	CIM> DIS or IOS with verification	Acceptable for subgingival cases
Mesial	DIS > IMS (Sectional trays improve access)	Acceptable for subgingival cases
Lingual	CIM	Avoid standalone DIT
Distal	DIS > IMS with verification	Avoid standalone IOS

Figures

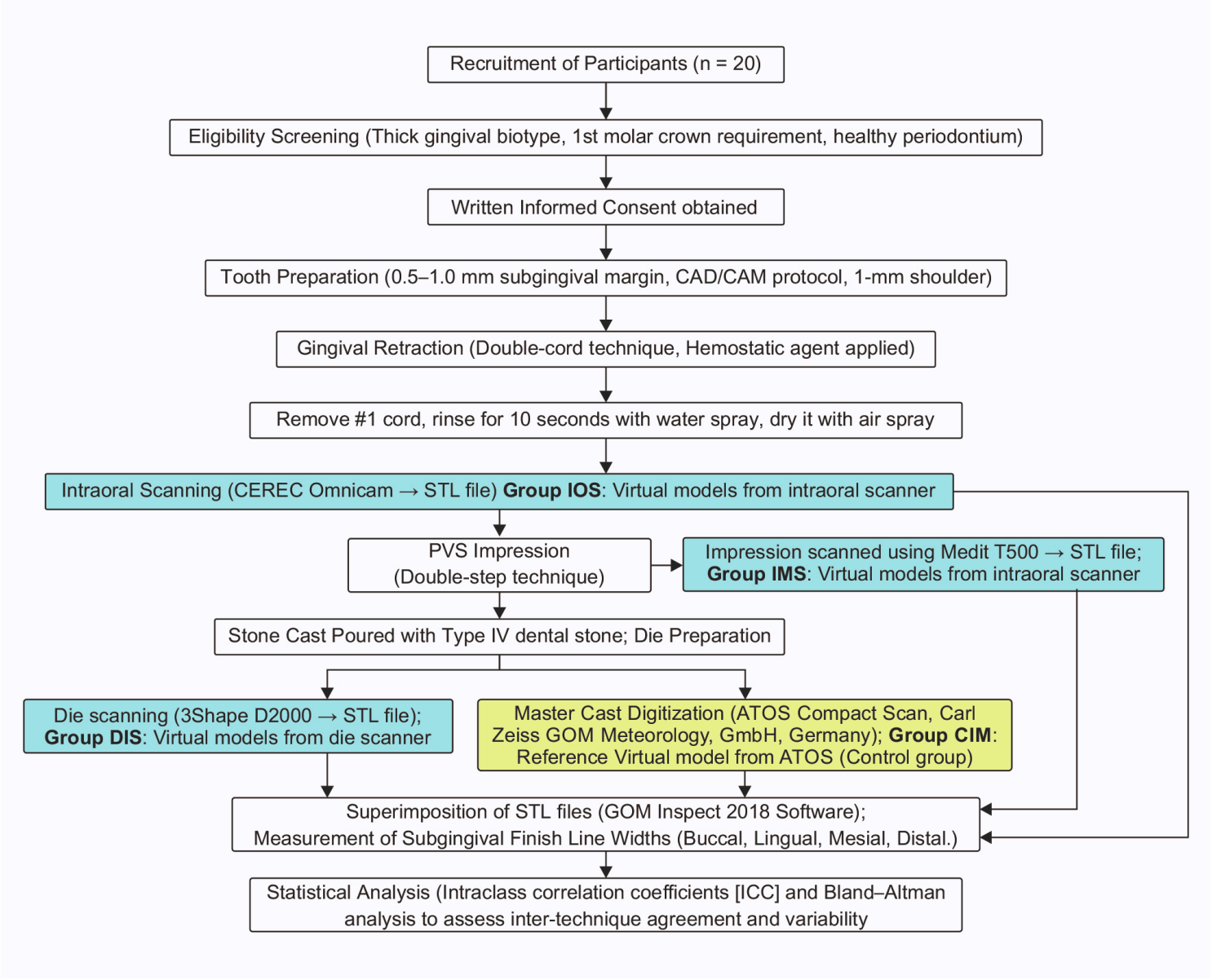
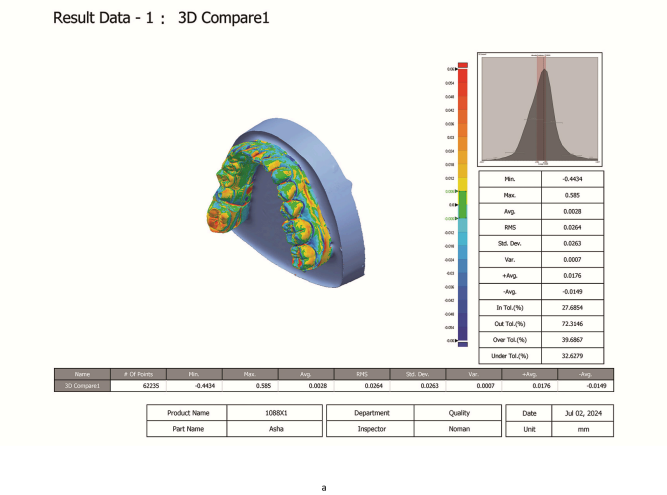
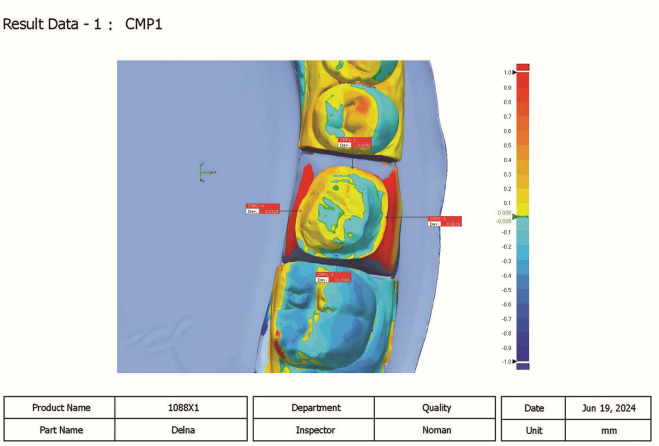


Figure 1

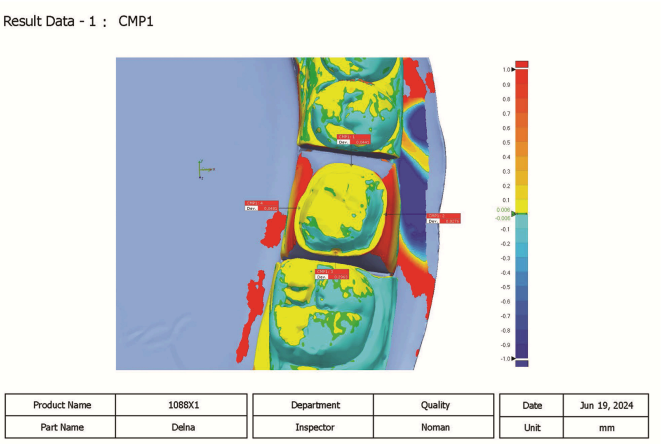
Workflow comparing digital and conventional impression techniques for subgingival finish line.



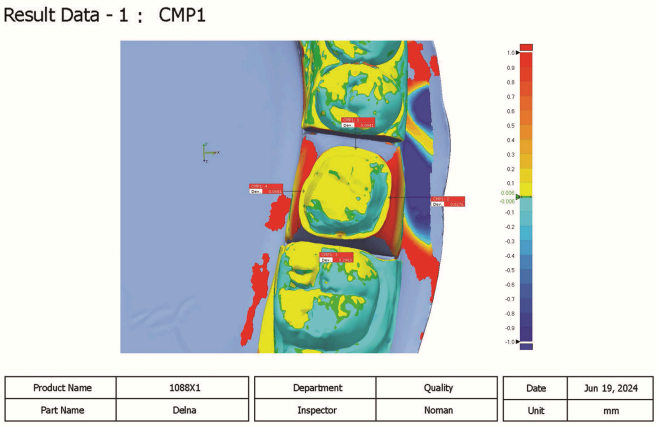
a



b



c



d

Figure 2

a. Superimposition of virtual dental models using best-fit algorithm.

b. Superimposition of intraoral scan (IOS) on reference scan (CIM) using best-fit algorithm.

c. Superimposition of impression scan (IMS) on reference scan (CIM) using best-fit algorithm.

d. Superimposition of die scan (DIS) on CIM using best-fit algorithm.

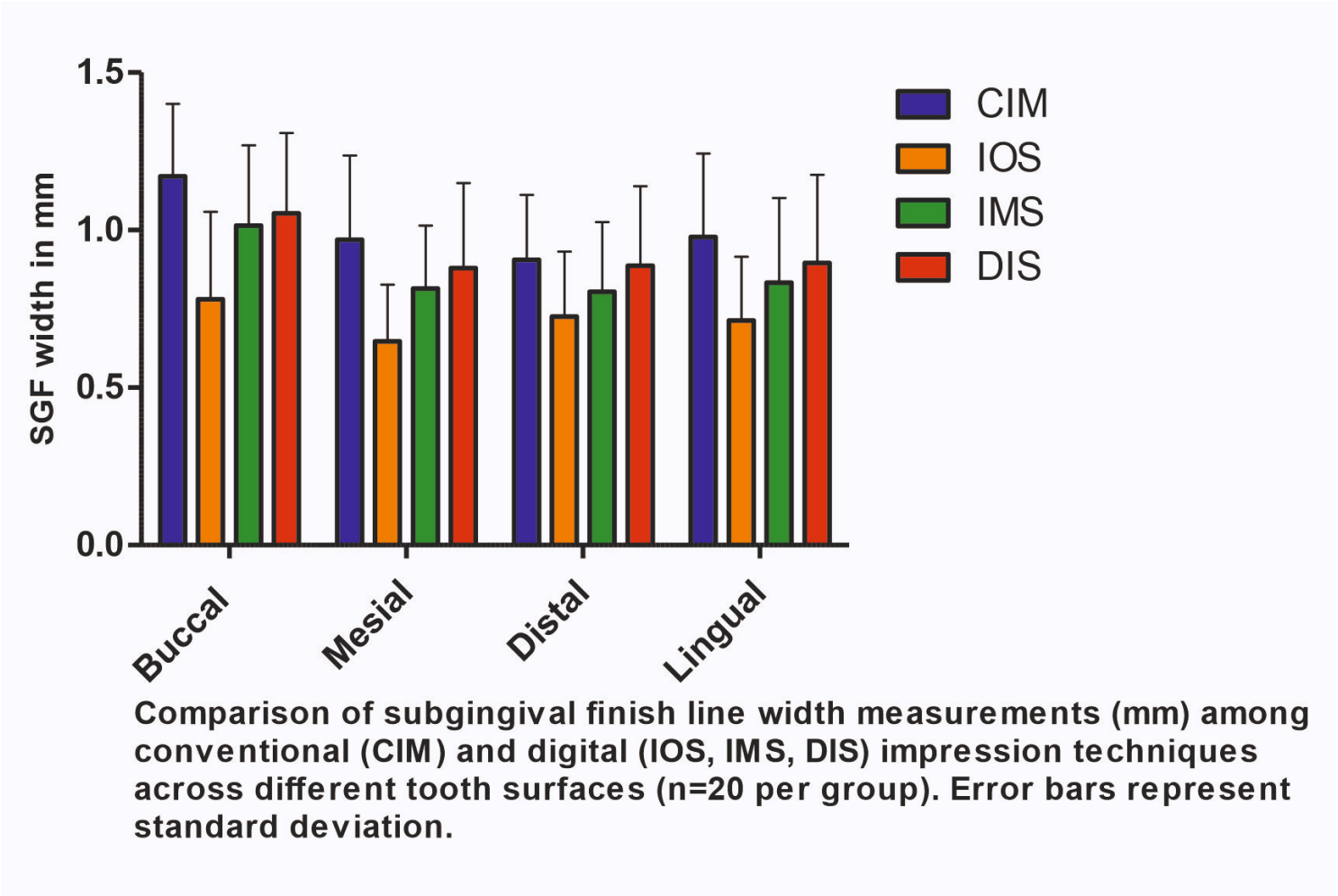


Figure 3

Comparison of mean SGFL widths (mm) at buccal, lingual, mesial, and distal aspects between CIM, IOS, IMS and DIS

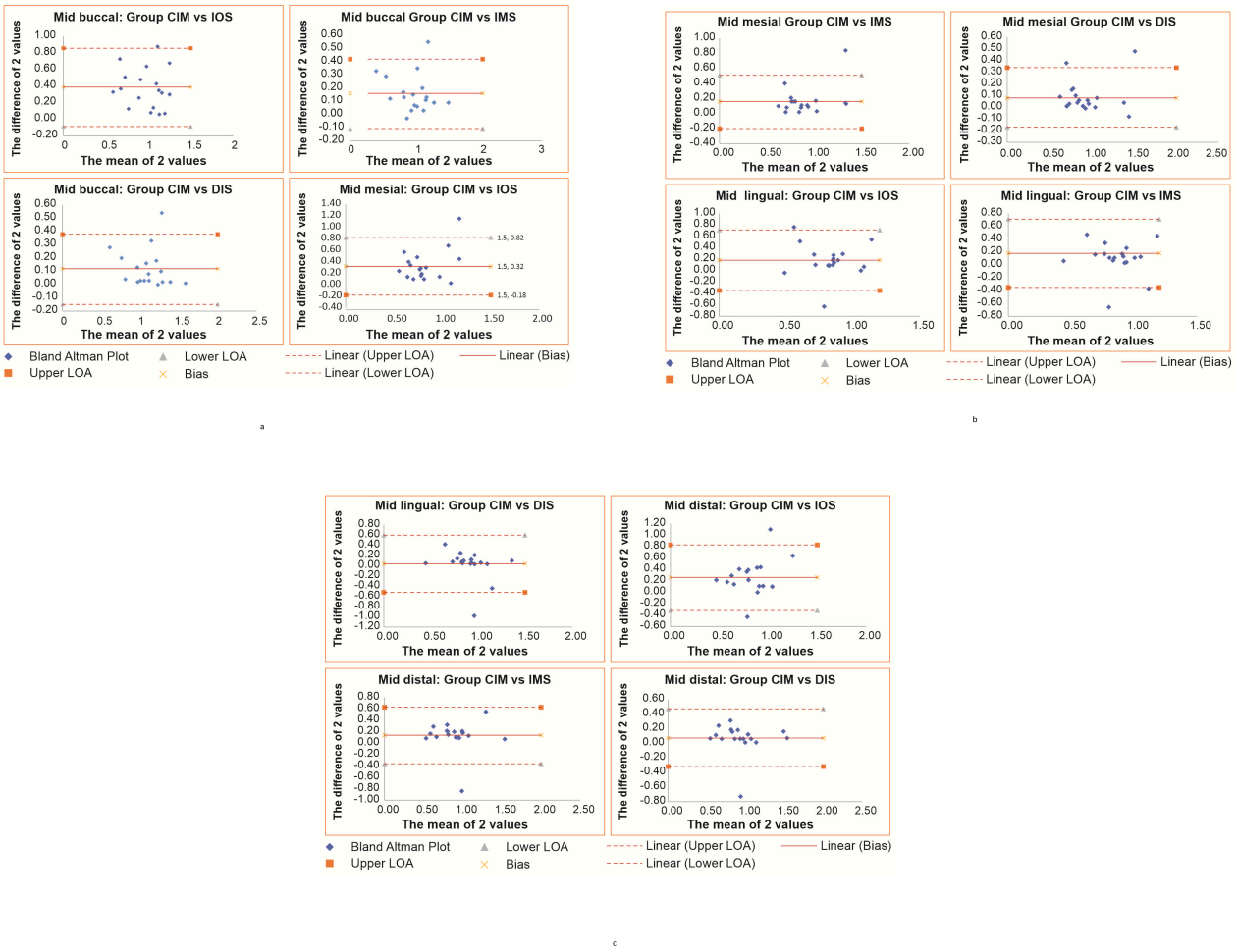


Figure 4

a. Bland-Altman plots comparing intra oral scanning, impression scanning and die scanning with conventional impression for subgingival finish line: Mid buccal – CIM vs IOS; CIM vs IMS; CIM vs DIS and Mid mesial – CIM vs IOS. Dashed lines represent limits of agreement (±1.96 SD).

b. Bland-Altman plots comparing intra oral scanning, impression scanning and die scanning with conventional impression for subgingival finish line: Mid mesial –CIM vs IMS; CIM vs DIS and Mid lingual – CIM vs IOS; CIM vs IMS. Dashed lines represent limits of agreement (±1.96 SD).

c. Bland-Altman plots comparing intra oral scanning, impression scanning and die scanning with conventional impression for subgingival finish line: Mid lingual –CIM vs DIS and Mid distal – CIM vs IOS; CIM vs IMS; CIM vs DIS. Dashed lines represent limits of agreement (±1.96 SD).

Supplementary Files

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- GraphicalAbstractN.jpeg