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Efficiency and geometric fidelity of library-selected anatomical prefabricated abutments and stock abutments relative to custom CAD-CAM abutments in posterior implant restorations

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PURPOSE. This study evaluated the clinical efficiency and geometric fidelity of the library-selected anatomical prefabricated abutments (LAPA) compared with custom abutments (CA) and stock abutments (SA) by using a novel sector-based deviation analysis (SBDA) method. **MATERIALS AND METHODS.** Two posterior single-implant cases, the mandibular left first molar and right second premolar, were selected for *in vitro* analysis. Twenty-four dental professionals (15 prosthodontic residents and 9 board-certified prosthodontists) performed three tasks: CA design, LAPA selection, and SA selection. The recorded time required for CA design and LAPA selection was compared. Overall geometric conformity was assessed using in-tolerance analysis (± 0.50 mm, ± 0.70 mm), and margin-level fidelity was evaluated by sector-based and vector-based deviation analyses. The Wilcoxon signed-rank test was used to evaluate the clinical efficiency and geometric fidelity at a significance level of $\alpha = 0.05$. **RESULTS.** LAPA required significantly less design time than the custom abutment (CA) ($P < .001$). Both LAPA and SA showed high overall conformity to CA within clinically acceptable limits. Sector- and vector-based analyses demonstrated that LAPA more closely replicated CA margin positions than SA, indicating superior morphological consistency with greater time efficiency. **CONCLUSION.** Within the limitations of this *in vitro* study, the library-selected anatomical prefabricated abutment showed a balanced performance between clinical efficiency and morphological fidelity. [J Adv Prosthodont 2025;17:392-405]

KEYWORDS
Digital workflow; Implant abutment; Clinical efficiency; Margin-level fidelity; Sector-based deviation analysis

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INTRODUCTION

Contemporary implant therapy emphasizes biologic stability and esthetic integration, where the contour and volume of the peri-implant soft tissue directly influence esthetic outcomes and patient satisfaction.[1-3] A key determinant of esthetic success lies in the emergence profile of the final restoration, which is influenced by the implant position and the design of the transmucosal abutment.[4-6] Once an implant has been placed in a prosthetically acceptable zone, the morphology and positioning of the abutment become central to shaping the peri-implant tissue and achieving a harmonious transition between the prosthesis and the gingiva.[7-9] In this context, the implant abutment serves not only as a structural connector but also as a biologically sensitive interface between the implant and the oral environment.

Stock abutments are widely used in clinical practice due to their ease of use, rapid availability, and manufacturing precision. Produced under standardized industrial conditions, these components offer high dimensional accuracy and consistent mechanical properties.[10-16] Because they do not require additional laboratory fabrication, they allow earlier delivery of the definitive prosthesis.[17] However, they may offer limited flexibility in cases requiring detailed optimization of soft tissue contours, margin positioning, or emergence profiles because stock abutments are available in fixed shapes and dimensions. Moreover, inadequate adaptation of the abutment to the gingival contour may complicate excessive cement removal, particularly when margins are placed subgingivally. These limitations can negatively affect esthetic outcomes, biologic stability, and hygiene maintenance.[18, 19]

To address these challenges, implant treatment has progressively evolved toward a more patient-specific approach in prosthetic design. Early efforts to individualize abutment morphology began with the use of UCLA-type abutments, which allowed casting of customized shapes using wax patterns and lost-wax techniques. While this approach offered greater design flexibility, it was technique-sensitive and carried risks of casting distortion, contamination, and technical errors during laboratory fabrication.[20,21] The subsequent development of digital workflows and computer-aided design and computer-aided manufacturing (CAD-CAM) technology enabled a more precise and reproducible method for fabricating custom abutments, marking a major transition toward fully digital, patient-tailored implant prosthetics using high-precision milling systems. This advancement enabled clinicians to control margin height, emergence profile, and abutment contour with much greater precision and repeatability. Custom abutments have thus become widely adopted in both implant restorations, particularly when soft tissue management and esthetic demands are critical.[18,19,22,23]

Despite their advantages, custom abutments also have limitations. Their fabrication process involves multiple steps, including digital designing, milling, and a post-milling procedure, each of which may introduce variability. The use of various software systems, the absence of standardized design protocols, and variations in milling machine calibration across clinics and laboratories can lead to discrepancies in the dimensional accuracy and surface quality of abutments.[12] Furthermore, contamination from milling debris, polishing compounds, or cast stone materials may remain on the abutment surface unless strict cleaning protocols are followed, which could compromise the implant-abutment connection or soft tissue response.[24-26]

Perhaps more importantly, the outcome of custom abutment design is often dependent on the skill and experience of the operator. Both dental technicians and clinicians must understand how to interpret soft tissue anatomy, position margins appropriately, and create an emergence profile that supports peri-implant tissue health. Inadequate design, such as excessive emergence angles or improper thickness of the transmucosal part, may increase the risk of peri-implant inflammation, plaque accumulation, or compromised soft tissue sealing. These risks highlight the need for a more standardized yet flexible solution that balances customization with manufacturing control.

In response to these needs, the library-selected anatomical prefabricated abutment (LAPA) has been introduced as a library-driven system intended to provide anatomical conformity without requiring full customization. This system provides clinicians with

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a digitally pre-designed library of anatomically contoured abutments that mimic the emergence profiles and soft tissue contours of custom abutments. The design is based on tooth-specific morphology, with multiple options available across mesiodistal widths, buccolingual depths, gingival heights, and abutment heights. By using this system, clinicians may select an abutment that closely matches the patient's soft tissue and prosthetic needs, eliminating the need for complex digital design or laboratory fabrication. Because these abutments are mass-produced under industrial standards, they retain the mechanical accuracy of prefabricated components while offering anatomical conformity. The selection process can be performed digitally or chairside, and the final abutment can be delivered without compromising on biologic or esthetic principles. This hybrid approach has the potential to streamline clinical workflows and reduce reliance on technician expertise.

While the LAPA system has been developed to combine the clinical efficiency of prefabricated abutments with the anatomical precision of custom designs, its clinical validity and performance have not yet been systematically verified. It remains unclear whether these anatomically pre-designed abutments can reliably reproduce the critical aspects of custom abutments, such as gingival margin contours and emergence profiles. Considering that accurate margin positioning is critical for maintaining peri-implant tissue health and facilitating cement removal, it serves as a meaningful parameter for comparative evaluation.

The present study was therefore designed to evaluate both the clinical efficiency and morphological fidelity of the LAPA system. Specifically, the time efficiency of LAPA selection was compared with that of conventional digital custom abutment design to assess workflow advantages. In addition, the morphological accuracy of LAPA was analyzed through a detailed three-dimensional (3D) to two-dimensional (2D) comparison with operator-designed custom abutments using a standardized sector-based deviation analysis (SBDA) framework, which enables reproducible assessment of margin conformity. The null hypothesis of this study was that there would be no significant difference between the LAPA and the stock abutment in terms of time efficiency and margin-level morphological conformity when compared with digitally designed custom abutments.

MATERIALS AND METHODS

Two posterior single-implant cases were selected for *in vitro* analysis: the mandibular left first molar (#36) and the mandibular right second premolar (#45). Each case exhibited average mesiodistal spacing, normal occlusal relationships, and no notable anatomical complications (Fig. 1). STL datasets were generated and imported into a dental CAD software program (DentalCAD 3.2 Galway; Exocad GmbH, Darmstadt, Germany) for standardized use across all participants. Twenty-four dental professionals participated in the study, including 15 prosthodontic resi-

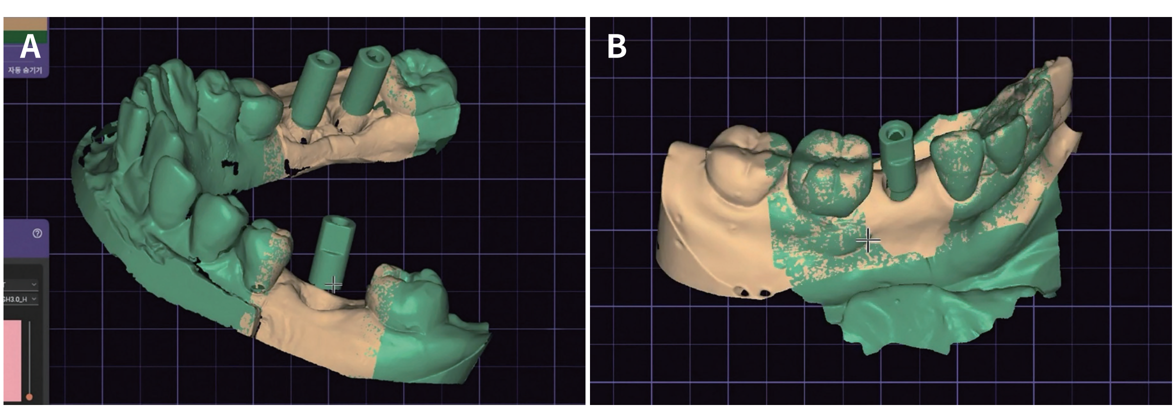

Fig. 1. Posterior single-implant cases used in this study: (A) mandibular left first molar (#36), (B) mandibular right second premolar (#45).

dents and 9 board-certified prosthodontists. Prior to the experiment, all participants received a 15-minute standardized tutorial on the use of the CAD software and selection protocols for LAPA abutments.

Each participant completed the following three tasks in both cases:

1. Custom abutment design: participants digitally designed a custom abutment (CA) based on the mucosal emergence contour and implant axis (Fig. 2A). 2. LAPA selection: participants selected the most appropriate LAPA (Smart abutment, Osstem Implant Co, Ltd, Seoul, Korea) using the manufacturer-provided software workflow. Each selection was performed interactively within the digital environment, based on patient-specific STL data and the integrated LAPA library (Fig. 2B). 3. Stock abutment selection: after completing the CA and LAPA tasks, participants selected a stock abutment (Transfer abutment, Osstem Implant Co, Ltd, Seoul, Korea) using manufacturer-provided catalogs and components. Each abutment was exported as an STL file. Task durations for CA and LAPA were recorded in seconds.

All STL datasets were analyzed using 3D inspection software (Geomagic Control X; 3D Systems, Cary, NC, USA). Each participant's LAPA and stock abutment (SA) data were superimposed onto their corresponding CA using local best-fit alignment based on the external surface above the implant abutment hex structure.

First comparison was performed on the superimposed abutments, focusing on the external surface region located coronal to the implant platform, while excluding the internal connection area. Surface deviation was quantified using the in-tolerance percentage, defined as the proportion of the abutment surface area within a predefined clinical deviation threshold. The primary threshold was set at ±0.50 mm, with ±0.70 mm applied for extended tolerance analysis (Fig. 3).

To evaluate margin-level conformity, a standardized sectoral mapping method was applied. A primary reference plane (Plane 0°) was defined by the most prominent midfacial point of each abutment and the implant long axis. Based on this plane, four additional radial planes were constructed at –90°, –45°, +45°, and +90°, all including the same implant axis to ensure anatomical consistency (Fig. 4A). These five planes divided the peri-implant region into consistent directional sectors: distal (D), distobuccal (DB), midbuccal (B), mesiobuccal (MB), and mesial (M) planes (Fig. 4B).

For each participant, five directional points (M, MB, B, DB, and D) were extracted per abutment. The linear distance between each corresponding point on the reference abutment (CA) and the test abutments (LAPA and SA) was measured. Points falling within the tolerance thresholds of ±0.3, ±0.5, and ±0.7 mm were counted for each participant.[27-31] This count indicated the number of margin points located within the specified deviation limits from the CA, providing a quantitative measure of buccal margin conformity for both LAPA and SA.

To quantify the directionality of margin deviation, each intersection point was measured horizontally from the implant long axis and vertically from the

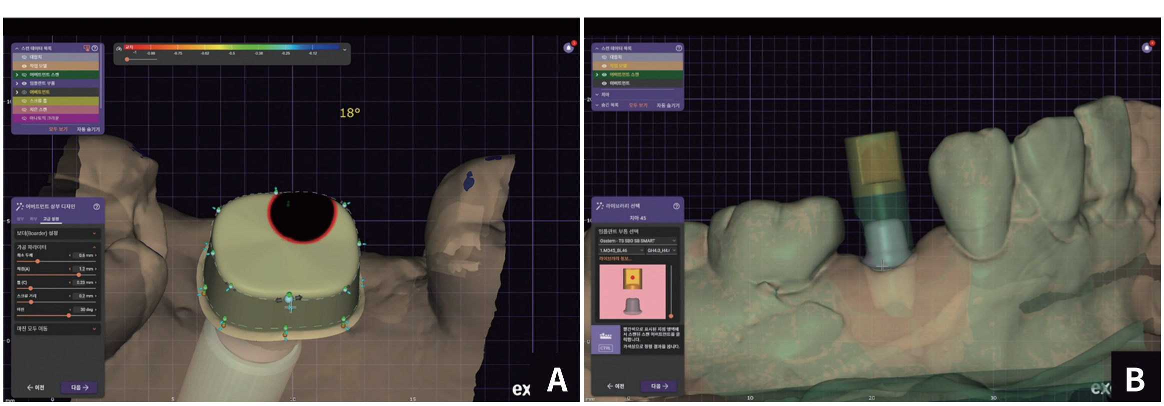

Fig. 2. Tasks performed by participants: (A) CA design, (B) LAPA selection.
CA, custom abutment; LAPA, library-selected anatomical prefabricated abutment.

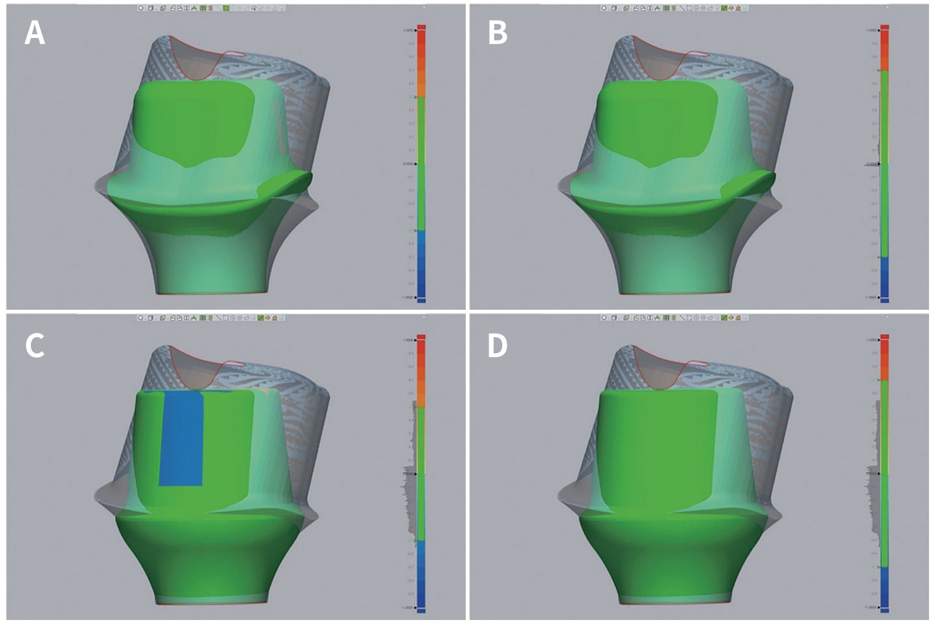

Fig. 3. Measurement of in-tolerance ratios for prefabricated abutments relative to the custom abutment at specified deviation thresholds: (A) LAPA at 0.5 mm tolerance, (B) LAPA at 0.7 mm tolerance, (C) SA at 0.5 mm tolerance, (D) SA at 0.7 mm tolerance. LAPA, library-selected anatomical prefabricated abutment; SA, stock abutment.

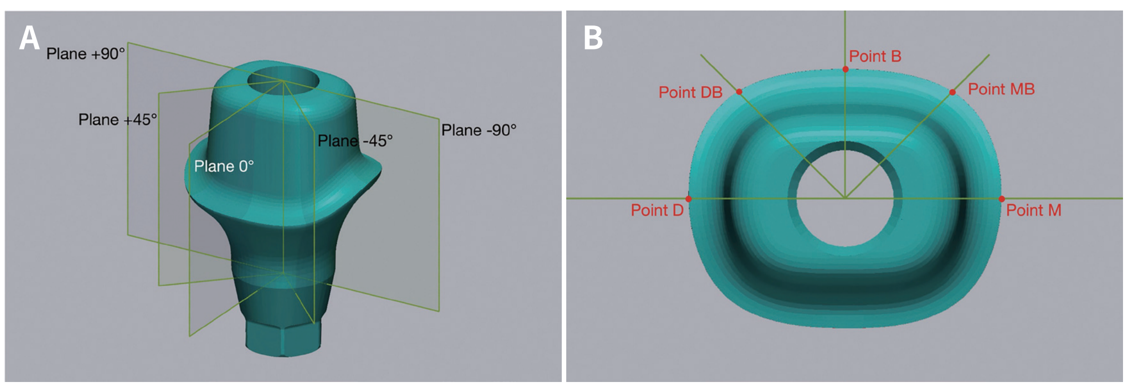

Fig. 4. Standardized sectoral mapping for margin-level conformity analysis: (A) establishment of the primary reference plane (Plane 0°) defined by the implant long axis and the midfacial point, followed by construction of four additional radial planes at –90°, –45°, +45°, and +90°, (B) five corresponding margin points (M, MB, B, DB, D) were generated by the intersection of these planes with the abutment surface.

implant platform plane (Fig. 5). For each direction, the distance ratio between the test abutment and the reference abutment was calculated. These ratios indicated the degree of conformity in horizontal and vertical directions.

The normality of the acquired data was assessed by using the Kolmogorov-Smirnov test and the Shapiro-Wilk test. Wilcoxon signed-rank test was used to evaluate the clinical efficiency, the overall abutment design tolerance, and margin fidelity. All statistical analyses were performed using a statistical software program (IBM SPSS Statistics, v29.0; IBM Corp., Armonk, NY, USA) ($\alpha = 0.05$).

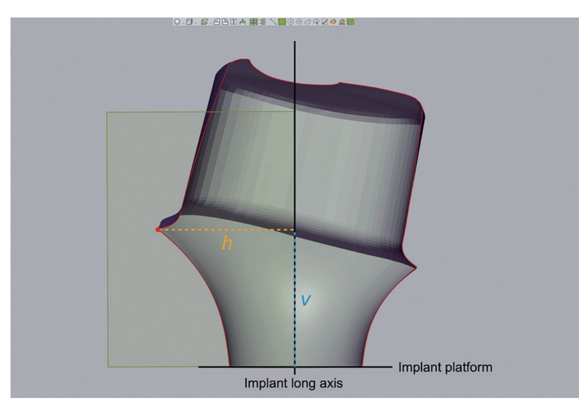

Fig. 5. Measurement of horizontal margin width (h) and vertical margin height (v), defined respectively as the distance from the implant long axis and the height from the implant platform.

RESULTS

The time required for abutment design or selection was measured using a standardized CAD workflow (Table 1). For CA design, the mean time was 229 ± 82 seconds for tooth #36 and 253 ± 116 seconds for tooth #45. In contrast, LAPA selection required 122 ± 68 seconds and 125 ± 61 seconds, respectively.

Wilcoxon signed-rank tests showed that LAPA selection required significantly less time than CA design for both positions ($P < .001$).

The overall geometric conformity of the LAPA and SA was evaluated using the in-tolerance rate, defined as the percentage of surface area falling within a specified deviation threshold relative to the CA (Table 2). At the ± 0.5 mm tolerance, the mean in-tolerance rate for the #36 abutments was 89.58 ± 3.97% for LAPA and 87.32 ± 6.34% for SA, showing no statistically significant difference between the two groups ($P = .145$). For the #45 abutments, the mean in-tolerance rate was 93.08 ± 5.50% for LAPA and 97.74 ± 2.75% for SA, with a statistically significant difference ($P < .001$). When the tolerance threshold was increased to ± 0.7 mm, both abutment types achieved 100% in-tolerance across all samples. These findings indicate that both LAPA and SA demonstrated high overall geometric conformity within clinically acceptable limits.

The conformity of buccal margin positions was evaluated by counting the number of corresponding points located within defined deviation thresholds (± 0.3 mm, ± 0.5 mm, and ± 0.7 mm) relative to the CA across five buccal sectors (Table 3). At the ±0.3 mm threshold, the LAPA showed 1.45 ± 1.06 points

Table 1. Comparison of time required for CA design and LAPA selection (seconds)

Tooth number	CA design	LAPA selection	*P* value
#36	229 ± 82	122 ± 68	< .001
#45	253 ± 116	125 ± 61	< .001

CA, custom abutment; LAPA, library-selected anatomical prefabricated abutment.

Table 2. In-tolerance rates of abutment evaluated at the 0.5 and 0.7 mm deviation threshold (%)

Tooth number	Tolerance (mm)	LAPA	SA	*P* value
#36	0.5	89.58 ± 3.97	87.32 ± 6.34	.145
	0.7	100	100	-
#45	0.5	93.08 ± 5.50	97.74 ± 2.75	< .001
	0.7	100	100	-

Values at the 0.5 mm threshold are presented as mean ± standard deviation, while all values at the 0.7 mm threshold reached 100%.
LAPA, library-selected anatomical prefabricated abutment; SA, stock abutment.

Table 3. Mean and standard deviation of the number of corresponding points on LAPA and SA margins falling within the tolerance threshold (0.3 / 0.5 / 0.7 mm) relative to the CA margin

Tooth number	Tolerance (mm)	LAPA	SA	*P* value
#36	0.3	1.45 ± 1.06	0.96 ± 0.91	.062
	0.5	3.13 ± 1.08	1.38 ± 1.06	< .001
	0.7	4.08 ± 0.88	2.75 ± 1.45	.006
#45	0.3	1.71 ± 1.43	0.92 ± 0.97	.024
	0.5	3.17 ± 1.52	1.25 ± 1.22	< .001
	0.7	4.25 ± 1.19	2.04 ± 1.40	< .001

CA, custom abutment; LAPA, library-selected anatomical prefabricated abutment; SA, stock abutment.

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within tolerance for #36 and 1.71 ± 1.43 for #45, compared with 0.96 ± 0.91 and 0.92 ± 0.97 for the SA (P = .062 for #36; P = .024 for #45). At ±0.5 mm, the corresponding values were 3.13 ± 1.08 for #36 and 3.17 ± 1.52 for #45 in the LAPA group, and 1.38 ± 1.06 and 1.25 ± 1.22 in the SA group (P < .001 for both sites).

When the tolerance was expanded to ± 0.7 mm, the LAPA recorded 4.08 ± 0.88 for #36 and 4.25 ± 1.19 for #45, whereas the SA showed 2.75 ± 1.45 and 2.04 ± 1.40, respectively (P = .006 for #36; P < .001 for #45).

The horizontal and vertical positions of the margin points for the LAPA and SA abutments were compared with those of the corresponding CA (Table 4, Fig. 6). In this analysis, horizontal and vertical ratios were calculated by dividing the respective coordinates of the test abutment by those of the CA. A ratio greater than 1 indicated a higher value than CA; a value less than 1 indicated a lower value.

In the horizontal dimension, the LAPA group exhibited ratios greater than 1 at most measurement points, whereas the SA group showed lower ratios. Statistically significant differences between the groups were observed at all sectors except for the buccal and distal sectors of #36 and the mesial and distal sectors of #45 (P < .05). In the vertical dimension, SA exhibited lower ratios than LAPA at all evaluated points, with statistically significant differences at every site except the buccal point of #45 (P < .05).

DISCUSSION

This study evaluated the clinical validity of library-selected anatomical prefabricated abutments (LAPA) based on two key parameters: design efficiency and margin-level morphological fidelity. Compared to custom abutments (CA), the use of LAPA resulted in a

Table 4. Comparison of horizontal and vertical ratios (relative distance ratios) between LAPA and SA with respect to CA at five margin points (M, MB, B, DB, and D) for teeth #36 and #45 (Mean ± SD)

Tooth number	Position	Factor	LAPA	SA	P value
#36	M	Horizontal	0.9092 ± 0.0778	0.8473 ± 0.0821	.015
		Vertical	1.0090 ± 0.0743	0.6968 ± 0.0873	< .001
	MB	Horizontal	1.0496 ± 0.0812	0.9369 ± 0.0933	< .001
		Vertical	0.9444 ± 0.0627	0.8174 ± 0.0982	< .001
	B	Horizontal	0.9809 ± 0.0820	0.9796 ± 0.0817	0.886
		Vertical	0.9363 ± 0.0603	0.8757 ± 0.0995	< .001
	DB	Horizontal	1.0346 ± 0.0596	0.9317 ± 0.0893	< .001
		Vertical	0.9177 ± 0.0771	0.7956 ± 0.0934	< .001
	D	Horizontal	0.9601 ± 0.0704	0.9078 ± 0.1069	.278
		Vertical	1.2589 ± 0.1116	0.8723 ± 0.1263	< .001
#45	M	Horizontal	1.0030 ± 0.1542	0.9759 ± 0.1302	.819
		Vertical	1.0039 ± 0.0768	0.7465 ± 0.1013	< .001
	MB	Horizontal	1.1430 ± 0.1815	0.9907 ± 0.1300	< .001
		Vertical	1.0351 ± 0.0465	0.9089 ± 0.1151	< .001
	B	Horizontal	1.0750 ± 0.1656	0.9728 ± 0.1075	< .001
		Vertical	1.0305 ± 0.0440	0.9625 ± 0.1096	.199
	DB	Horizontal	1.1148 ± 0.1445	0.9737 ± 0.0884	< .001
		Vertical	0.9316 ± 0.0588	0.8031 ± 0.0885	< .001
	D	Horizontal	1.0193 ± 0.1189	0.9968 ± 0.0618	.668
		Vertical	1.0103 ± 0.0541	0.7563 ± 0.0922	< .001

LAPA, library-selected anatomical prefabricated abutment; SA, stock abutment; M, mesial; MB, mesiobuccal; B, buccal; DB, distobuccal; D, distal.

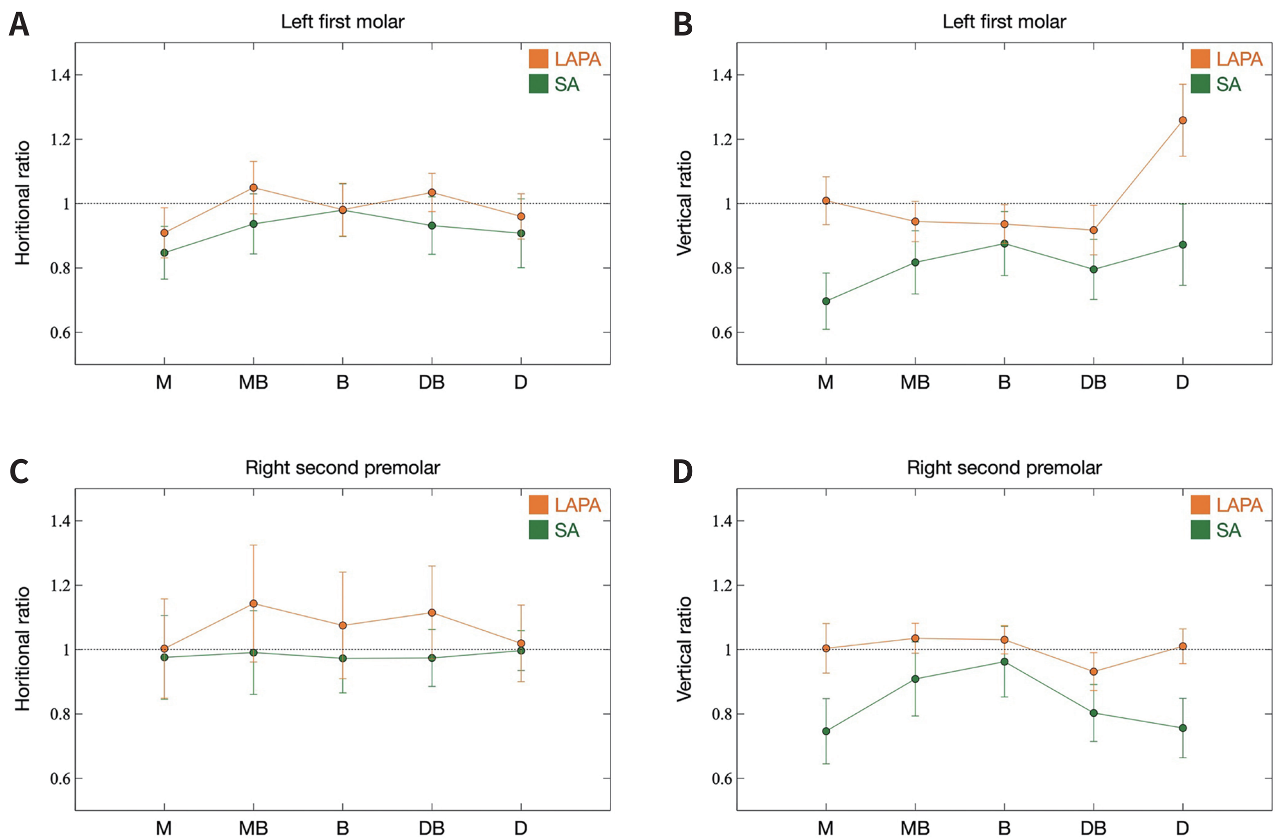

Fig. 6. Comparison of horizontal and vertical conformity ratios between LAPA and SA relative to CA at five margin points (M, MB, B, DB, and D). The dotted line at ratio = 1.0 represents the reference custom abutment, while each data point indicates the relative horizontal or vertical position of the prefabricated abutments. (A) Horizontal ratios for #36, (B) Vertical ratios for #36, (C) Horizontal ratios for #45, and (D) Vertical ratios for #45. Error bars indicate standard deviation.

significantly reduced design time. In addition, LAPA demonstrated morphological similarity to CA when compared with conventional stock abutments (SA), particularly in buccal margin regions. Based on these findings, the null hypothesis was rejected.

Wilcoxon signed-rank tests confirmed that LAPA selection required significantly less time than CA design, indicating that LAPA offers greater clinical efficiency in practice. In this study, time measurement for CA design included the margin delineation, axis setting, and design of the transgingival portions of the abutment. In practice, the custom workflow also involves additional steps, such as crown arrangement, which were not included in the measured design time, suggesting that the actual total time required for CA design would be even greater.

Following the demonstrated time efficiency of LAPA over CA, the next phase of this study focused on evaluating the overall geometric conformity of LAPA relative to operator-designed custom abutments. Given that each CA and LAPA pair inherently exhibits distinct design origins, direct surface-to-surface comparison between the two is methodologically limited. To overcome this limitation, the analysis was conducted by comparing LAPA to a conventional prefabricated SA, both of which are non-customized components designed to reflect standardized anatomical contours. Both LAPA and SA demonstrated high geometric fidelity to CA, with in-tolerance percentages exceeding 87% at the ± 0.50 mm threshold. This tolerance value is widely accepted in the literature and clinical practice as a benchmark for implant abutment fit. Under

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the more lenient ± 0.70 mm threshold, both LAPA and SA achieved a 100% in-tolerance rate across all participants, indicating that every participant-generated CA was morphologically comparable to the prefabricated counterparts within this clinically acceptable range.

The selection of tolerance thresholds was based on both technical constraints and biological relevance. A ± 0.30 mm range reflects the upper limit of precision typically achieved in CAD-CAM workflows, encompassing scanning and milling variability.[27] The ± 0.50 mm threshold has been widely accepted in the literature as the clinical limit for subgingival cement removal and peri-implant soft tissue maintenance.[28,29] The ± 0.70 mm range accounts for biologic remodeling phenomena, including dimensional changes in peri-implant tissues during healing.[30,31] These findings support the premise that the newly proposed LAPA system achieves an overall design precision equivalent to conventional prefabricated abutments and falls well within accepted clinical parameters. From a clinical perspective, these results suggest that LAPA provides an appropriate level of geometric accuracy for general use, reinforcing its feasibility as a stable and compatible initial stage of the digital abutment workflow.

While overall abutment geometry provides a general assessment of shape fidelity, it does not fully capture the clinical relevance of abutment selection. In practice, the precise location and reproducibility of the abutment margin are critical, especially in esthetically sensitive regions. Facial margin positioning, in particular, has been shown to significantly influence esthetic outcomes in implant prosthetics. Also, from a digital workflow perspective, the delineation of the abutment margin serves as the foundational step in CA design, directly influencing both abutment morphology and the final crown contour. Similarly, SA selection is typically guided by gingival height and marginal configuration. Accordingly, margin morphology represents the most decisive factor in both abutment design and selection.

To address this, the present study introduced a novel analytic framework, Sector-Based Deviation Analysis (SBDA), to quantify margin-level fidelity. This approach divides the abutment into five angular sectors and evaluates the positional deviation of margin points in both horizontal and vertical directions. It further quantifies conformity using predefined tolerance thresholds and visualizes direction-specific discrepancies, thereby providing a localized and clinically meaningful assessment of margin accuracy. Across all evaluated thresholds, LAPA exhibited consistently higher within-tolerance rates than SA, with statistically significant differences observed in all cases except at the 0.30 mm threshold for tooth #36. SA demonstrated lower reproducibility, with several cases failing to achieve even three matching points under the more lenient ± 0.70 mm threshold. By comparison, LAPA consistently achieved three or more matching points at the primary ± 0.50 mm threshold in both premolar and molar designs and averaged four or more points within the ± 0.70 mm range, underscoring its superior margin conformity. These results suggest that LAPA more accurately replicates the buccal margin positioning of CA, a region considered critical for esthetic integration and peri-implant tissue health. The margin configuration observed in LAPA appears to reflect core principles of custom abutment design, including alignment with soft tissue contours. This supports the anatomical validity of LAPA's prefabricated form and its potential for clinically reliable margin positioning.

Vector-based analysis was performed to evaluate the horizontal and vertical deviation of peri-implant margin positions across five buccal sector points, which were divided to reflect the differing clinical importance of each sector with respect to esthetic outcomes and peri-implant tissue health. The horizontal and vertical positions of the margin points for the LAPA and SA were compared with those of the corresponding CA. In this analysis, a horizontal factor greater than 1 indicated a margin located more buccally relative to the implant axis than the CA, whereas a value less than 1 represented a margin positioned closer to the implant axis. A vertical factor greater than 1 indicated a supragingival margin relative to the CA, while a value less than 1 indicated a subgingival margin.

Point B, corresponding to the midbuccal sector, represents a clinically critical site in implant esthetics due to its influence on facial contour and soft tissue integration. In terms of the horizontal width of the abutment margin, both LAPA and SA in the #36 design exhibited values slightly below that of the reference CA (1.0000), with no significant difference observed between the groups. In the #45 design, LAPA and SA also approximated the CA, suggesting minimal deviation from the intended horizontal profile. This outcome may be attributed to the decision-making priorities of the participants, who consisted of prosthodontic residents and board-certified prosthodontists. When selecting prefabricated abutments, these clinicians tended to emphasize the stability of the facial contour and the achievement of esthetic harmony. Consequently, the midfacial abutment-crown margin (Point B) was consistently adopted as a primary reference point, resulting in both LAPA and SA selections converging toward the corresponding margin location of the operator-designed custom abutment.

For the vertical position of the abutment margin point B, all test abutments were positioned subgingivally relative to the CA in the #36 case. However, LAPA margins at this site exhibited a position significantly closer to the CA compared with SA. This finding suggests that in molar cases, if horizontal stability is prioritized, the anatomically contoured design of LAPA allows for a margin position that more closely approximates the vertical configuration of the custom abutment. In the #45 case, the margin at point B demonstrated slightly supragingival positioning with LAPA, whereas SA remained subgingival. However, these differences did not reach statistical significance. These findings suggest that both LAPA and SA maintain overall horizontal consistency with the CA in the midbuccal region. Minor variations in vertical positioning may reflect differences in the prefabricated emergence profile of each abutment type but did not substantially affect positional fidelity at this esthetically sensitive site.

The proximal margins, positioned at points M and D, generally carry a lower esthetic priority compared to the buccal aspect; however, they remain clinically relevant due to their influence on gingival contour and soft tissue integration. Given the naturally scalloped morphology of the proximal gingiva, custom abutments usually feature a higher vertical margin position in the proximal site compared to the midfacial aspect. In terms of the horizontal width, SA exhibited narrower margin widths than LAPA at both proximal sites, although this difference reached statistical significance only at Point M in the #36 case. In terms of vertical margin height, a consistent pattern was found. LAPA exhibited slightly greater vertical values, corresponding to a more supragingival margin relative to the CA, whereas SA margins were positioned distinctly subgingivally. Specifically, LAPA demonstrated vertical ratios that were nearly equivalent to those of the CA, measuring 1.0090 at point M in #36, and 1.0039 and 1.0103 at points M and D in #45, respectively. In contrast, SA exhibited markedly lower ratios at both sites (0.6768 and 0.7956 in #36; 0.7456 and 0.7653 in #45), indicating deeper subgingival placement. This subgingival margin positioning in SA may pose clinical challenges, such as increased difficulty in cement removal and compromised peri-implant hygiene. Conversely, LAPA's anatomical design allows for more favorable margin emergence, potentially supporting better clinical maintenance and soft tissue health.

Notably, at point D in the #36 case, LAPA exhibited a markedly supragingival margin position, with a vertical ratio measured at 1.2589. This discrepancy may be attributed to a mild mesial inclination of the implant in this case. Given LAPA's bilaterally symmetric emergence profile, mesially tilted implants may result in relatively elevated distal margin positions. As margin selection typically emphasizes the buccal and mesial zones for esthetic reasons, the resulting supragingival positioning at distal sites can enhance cement removal and maintenance accessibility while exerting minimal esthetic compromise. This observation is consistent with commonly reported anatomical patterns where natural teeth and implants often present with a slight mesial inclination. The anatomical design of LAPA thus offers potential advantages in maintaining peri-implant tissue health, especially in the proximal regions.

The point MB and DB points represent transitional zones connecting the esthetic (midfacial) and hygienic (proximal) regions. These sites play an important role in maintaining overall margin continuity and ensuring the integrity of the emergence profile. At these transitional points, LAPA generally exhib-

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ited slightly greater horizontal margin width than the CA, whereas SA showed smaller widths relative to the reference. Vertically, both types of prefabricated abutments were positioned subgingivally; however, LAPA demonstrated a vertical margin position more closely approximating that of the CA. This pattern appears consistent with the gradual morphological transition observed across the M, B, and D points, reflecting the natural contour progression of the abutment-crown interface. Unlike SA, which presented a narrower and more confined margin form, LAPA maintained a sufficient horizontal width and an anatomically appropriate vertical level. Such characteristics contribute not only to improved esthetic harmony but also to favorable peri-implant tissue health through a more natural emergence profile.

This study analyzed two posterior single-implant cases, a molar (#36) and a premolar (#45), to evaluate potential variations in margin behavior according to anatomical site. Across both posterior cases, LAPA showed margin positions more closely aligned with CA than SA, particularly in the molar case. In the premolar case, both LAPA and SA demonstrated values close to CA in both the horizontal and vertical dimensions, with LAPA showing slightly higher values and SA generally presenting lower ones. This trend may be attributed to the anatomical characteristics of premolars. In this region, the crown morphology is relatively square, with similar mesiodistal and buccolingual dimensions. Additionally, the discrepancy between implant platform diameter and crown emergence is smaller than in molar sites. As a result, the morphological variation captured by LAPA and SA is inherently more limited, and differences between groups may be less pronounced.

Nevertheless, vertical margin position remained a differentiating factor. While SA consistently positioned margins subgingivally at both mesial and distal sites, LAPA margins were either aligned with or slightly supragingival to the CA, reflecting a more favorable emergence profile for maintenance and cement removal. In contrast, the molar region exhibits greater mesiodistal width and more variable implant-to-crown dimensional ratios. In such anatomically complex sites, a standardized SA design may introduce discrepancies in emergence profile. The anatomical adaptation present in LAPA becomes more advantageous in these cases, offering a closer match to the individualized geometry of CA.

Taken together, LAPA exhibited a balanced and consistent margin design pattern that preserved both esthetic alignment and hygienic accessibility. The advantage was not limited to mean deviation metrics but was particularly evident in anatomically and clinically significant regions. These findings highlight the selective superiority of LAPA over SA in replicating the clinically desirable contours of custom abutments, particularly in molar sites where anatomical variability is greater.

The proposed LAPA system demonstrated a balanced integration of three critical factors for clinical abutment selection: overall geometric conformity, workflow efficiency, and margin-level fidelity. Compared to conventional stock abutments (SA), LAPA offered anatomical accuracy, particularly in reproducing clinically relevant margin contours. At the same time, its library-guided selection process enabled a more streamlined workflow relative to fully customized abutment design, reducing operator burden and procedural time without compromising morphological quality. From a clinical perspective, LAPA presents as a viable alternative that serves as an intermediary between SA and CA. Its design characteristics support both esthetic demands and peri-implant soft tissue health, offering reproducible outcomes that are especially valuable in high-throughput or multi-operator environments. In cases where simultaneous esthetic precision and maintenance accessibility are required, such as posterior single-implant restorations, LAPA may serve as a practical solution that supports predictable prosthetic outcomes.

This study introduced a sector-based deviation analysis (SBDA) framework that enabled quantifiable comparison of three-dimensional abutment geometry through two-dimensional sectoral reduction. By segmenting the peri-implant region into anatomically defined planes and applying both threshold-based (within-tolerance) and vector-based (Δv, horizontal/vertical ratios) analyses, the methodology facilitated comprehensive evaluation of spatial conformity with high clinical interpretability. The layered analytical strategy incorporated multiple quantitative metrics and pointwise in-tolerance percentages, allowing for robust triangulation of morphological fidelity. In addition, the use of actual dental practitioners, especially prosthodontists as participants, enhanced ecological validity, ensuring that the findings reflect realistic behaviors within a clinical digital workflow context.

This study utilized actual clinical cases to enhance contextual relevance. However, the limitations of this study include its *in vitro* nature, which did not account for biological variables such as soft tissue response or healing dynamics. Additionally, the findings are limited to a single implant case, which may restrict generalizability across different implant-abutment interface designs. A standardized reference abutment design could not be established for comparison. The design of custom abutments (CA) inherently reflects each operator's individual treatment philosophy and esthetic priorities, resulting in considerable variability among designs. However, since no single ideal custom abutment design can be universally defined, evaluating margin fidelity relative to each operator-specific design was considered a reasonable approach within the context of this study. Furthermore, as the primary focus of this study was margin fidelity, other clinically significant aspects, such as emergence profile, crown form, and screw access orientation, were not evaluated. Moreover, this study focused on posterior implant restorations, specifically premolar and molar cases. However, anterior implant restorations were not included, as they often require advanced soft tissue management, which was beyond the scope of this study. In such cases, an evaluation based solely on margin fidelity may not be sufficient, and further clinical considerations would be necessary.

Future investigations should include clinical *in vivo* assessments to evaluate peri-implant soft tissue response and long-term biological stability according to the type of abutment selected. Expanding the study across various implant-abutment connection types and platform designs would enhance generalizability and clinical applicability. Further evaluation of the biomechanical behavior of abutment designs, including preload stability, screw loosening tendencies, and resistance to functional loading, is warranted. The current sector-based deviation analysis (SBDA) framework may be adapted to assess broader morphological characteristics, such as emergence profiles and crown contours. Additionally, the present dataset may serve as a foundational reference for developing artificial intelligence models that automate anatomically guided abutment selection within digital workflows.

This study demonstrated that LAPA exhibits high overall geometric conformity within clinically acceptable tolerances. The LAPA workflow showed time efficiency and a higher degree of margin positional fidelity compared with custom abutments. This experiment was conducted in a crossover design to control for learning effects, minimizing potential bias from task order. Clinically, LAPA contributes to workflow standardization and may be more suitable for less experienced clinicians who are less familiar with digital workflows. It allows clinicians to select chairside abutments, enabling direct communication of the chosen component to the dental laboratory and thereby improving clinical efficiency. Additionally, the LAPA workflow bypasses post-design milling and finishing steps, reducing both time requirements and the potential for fabrication-induced errors. Though not captured in the design-time analysis, these steps represent further time- and accuracy-related advantages. In insurance-based clinical settings, particularly in countries where reimbursement is limited to prefabricated abutments and not custom abutments (e.g., the Republic of Korea), the ability to reduce chairside and design time may yield substantial practical benefits. Moreover, in multi-operator environments, the use of LAPA may enhance reproducibility and predictability, contributing to greater standardization across digital workflows.

Overall, LAPA may serve as a practical alternative that balances clinical efficiency and morphological accuracy, particularly in posterior single-implant scenarios. However, the present findings are based on geometric evaluations, and further studies are needed to assess the mechanical stability and biological outcomes associated with the use of LAPA.

CONCLUSION

Within the limitations of this *in vitro* study, the library-selected anatomical prefabricated abutment showed a balanced performance between clinical efficiency and morphological fidelity. The findings suggest that anatomically guided prefabricated abutments may serve as a feasible option within the digital workflow, providing a level of standardization while maintaining reasonable adaptation to peri-implant morphology. LAPA demonstrated the potential to complement existing abutment selection strategies rather than to replace them, particularly in routine posterior implant restorations. Further clinical and biomechanical studies are necessary to validate these findings and to assess long-term biological responses associated with its use.

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