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Comparative cleaning efficacy of interdental brushes with different head shapes using 3D-Printed Models: An in vitro study

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ABSTRACT: Background: Good oral hygiene is essential for periodontal health and interdental aids have become a mandate, specifically in maintaining hygiene in interproximal regions inaccessible to toothbrush bristles. However, the effect of the brush head shape on the cleaning efficacy is still unknown. This study evaluated the cleaning efficacy of interdental brushes with different head shapes using CAD software and 3D printer.

Methods: 3D printed dental models with embrasure sizes of 0.7 mm, 0.8 mm and 1.2 mm were fabricated. Artificial plaque was prepared and uniformly applied to the interproximal surfaces of the molars to simulate clinical conditions. The cleaning of each model was performed with IDBs with trapezoidal, rectangular and diamond head shapes according to standard protocols. Digital photographs of the pre- and post-cleaning were taken and plaque removal was quantified by pixel-based image analysis.

Results: A statistically significant difference in the cleaning efficacy among the three interdental brush head shapes was observed across all embrasure sizes (p-value <0.001), with the trapezoidal head achieving the greatest efficacy compared to the rectangular and diamond heads.

Conclusion: The present study emphasises the importance of interdental brush head design on plaque removal efficacy in different embrasure sizes. The use of 3D printed

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dental models offered a standardized and reproducible evaluation of the interdental cleaning efficacy and a controlled simulation of clinical conditions.

1. INTRODUCTION

One of the main etiological factors in the development of periodontal diseases is dental pathogenic plaque, especially due to poor oral hygiene practices (Kim, Song and Lee, 2022). Effectively removing interproximal plaque disrupts the dental biofilm and helps maintain gingival health. Mechanical plaque control remains the cornerstone not only in preventing periodontal disease but also in its treatment and long-term maintenance. Improved personal oral hygiene has been shown to result in significant reduction of the incidence and severity of gingival inflammation. Toothbrushes continue to be the most common means of mechanical plaque removal; however, they are primarily effective on the buccal, lingual and occlusal surfaces with limited ability to clean interproximal areas (Guzeldemir-Akcakanat, 2020). As a result, interdental cleaning aids (ICAs) have become a necessity and current evidence suggests that interdental brushes (IDBs) are superior to other cleaning aids such as wooden sticks and dental floss (Christou *et al.*, 1998). The choice of IDBs should be adapted to the tooth morphology to optimize cleaning efficiency and minimize the risk of damage to enamel or gingival tissue (Slot, Valkenburg and Van der Weijden, 2020).

Since their inception in the 1960s, IDBs have evolved considerably. IDB selection is guided by the passage hole diameter (PHD) specified in ISO 16409:2016, typically ranging from 0.7 mm to 2.9 mm in routine clinical practice (Sekundo, Hans and Staehle, 2020). A cross-sectional study found that approximately 80.6% of interdental sites required smaller diameter brushes of approximately 0.6–0.7 mm in diameter (Carrouel *et al.*, 2016). Randomized clinical trials have shown that IDBs remove more supragingival plaque from interproximal sites than dental floss (Rösing *et al.*, 2006).

To better assess their efficacy, especially in anatomically complex regions like the human dentition, digital tools such as dental CAD/CAM and 3D printing have been used. The efficiency of plaque removal and insertion force of different interdental brush geometries, including cylindrical, conical, triangular and waist-shaped designs, have been reported in previous studies (Wolff *et al.*, 2006; Larsen *et al.*, 2017; Baumgartner *et al.*, 2019). However, the role of brush head configuration in initial insertion, adaptation to the interdental space and subsequent cleaning efficacy remains insufficiently explored. Therefore, the present study aimed to evaluate the cleaning efficacy of interdental brushes with diamond, rectangular and trapezoidal head shapes under standardised conditions using 3D printed models, which offer advantages such as precise control over embrasure dimensions, reduced anatomical variability and reproducibility of experimental conditions (Kim, Song and Lee, 2022).

2. MATERIALS AND METHODS

2.1 Study Design

This in-vitro study was conducted between October 2025 to November 2025 in the department of Periodontics, Sri Ramachandra Institute of Higher Education and Research.

2.2 Ethical Approval

The study protocol was approved by the institutional Ethics committee of Sri Ramachandra Institute of Higher education and Research Porur, Chennai (IECNO: CSP/25/SEP/167/454)

2.3 Study Material

Three different 3D printed models were fabricated using a 3D printer and photopolymer resin, each representing interdental embrasure size of 0.7 mm, 0.8 mm and 1.2 mm (Kim, Song and Lee, 2022). Zirconia crowns were added to the models to resemble the anatomical form and the tooth-like optical appearance of natural teeth (Denry and Kelly, 2008). Artificial plaque was made by mixing water with Staedtler Lumocolor permanent marker ink (Bertl, 2021). Interdental brushes (IDBs) with three different head shapes such as diamond, trapezoidal, and rectangular were selected for evaluation. (Figure 1)

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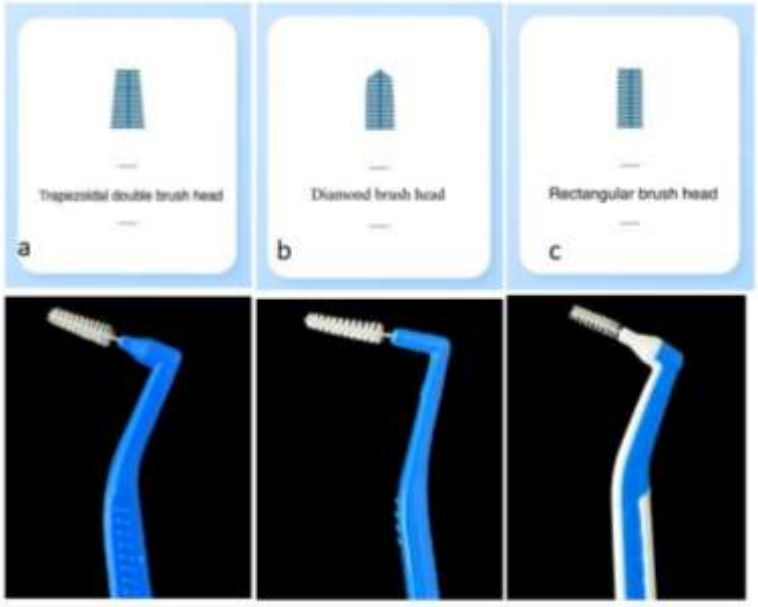


Figure 1: Interdental brush head shapes. (a) Trapezoidal brush head (b) Diamond brush head (c) Rectangular brush head

2.4 Model preparation

Teeth 36 & 37 on a typhodont model were prepared with a round-end, tapered diamond bur (Figure 2) and scanned using iTero intra oral scanner to obtain STL file to be processed on the CAD program. (Figure 3).



Figure 2: Tooth preparation i.r.t. 36 and 46. (a) Before preparation (b) During preparation (c) After preparation

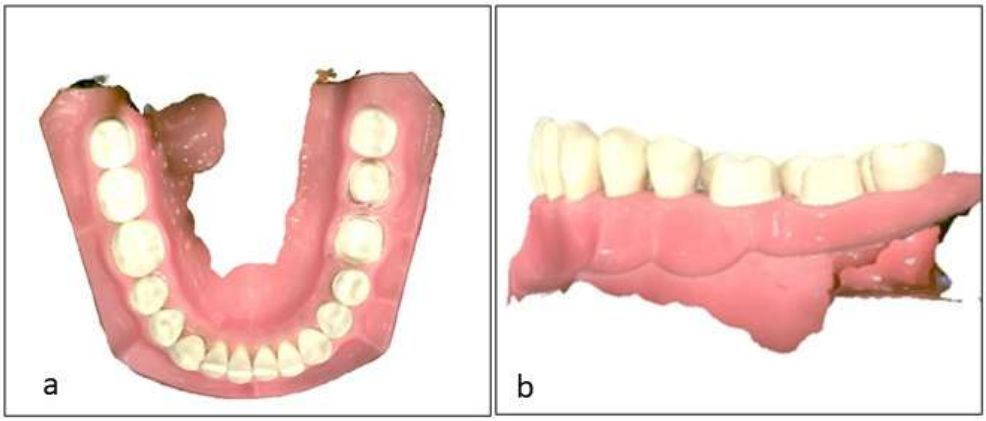


Figure 3: Scanned images of dentiform #36 and #37 using iTero® intra-oral scanner. (a) Front view (b) Side view

The zirconia crowns were designed, milled & sintered to fit the respective embrasure variations. The segment containing teeth 36 & 37 was made removable with interlocking features for easy removal and testing using Exocad software. Embrasure sizes 0.7mm, 0.8mm and 1.2mm were standardised digitally. (Figure 4) The third quadrant of the model was digitally segmented using CAD software and 3D printed. (Figure 5)

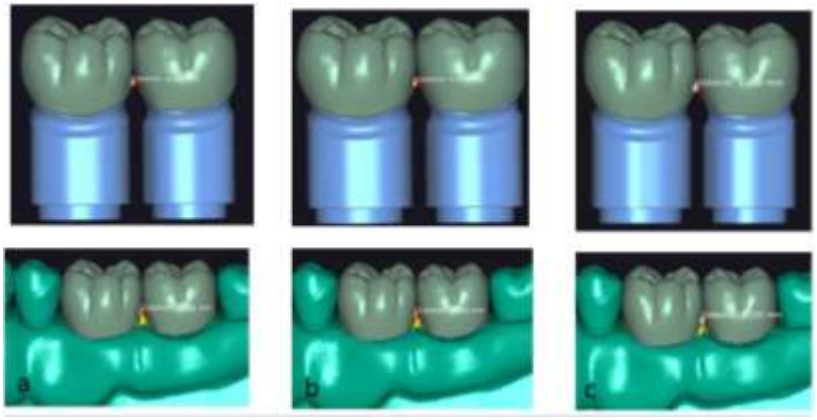


Figure 4: Digitally predetermined interdental embrasure sizes on 3D-printed models. (a) 0.7mm (b) 0.8mm (c) 1.2mm

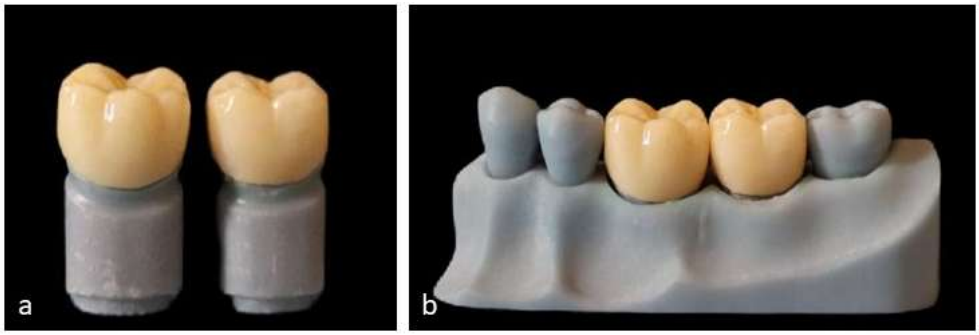


Figure 5: Representative images of the 3D model. (a) segment containing 36 & 37 was made removable with interlocking features (b) digitally segmented third quadrant of the model using CAD software and 3D printer with zirconia crowns on 36 and 37.

2.5 Preparation and application of artificial plaque and cleaning procedure:

Artificial plaque was prepared by a mixture of wheat flour, water and red sustainable ink (Staedtler Lumocolor permanent marker) (Bertl, 2021), to mimic the dental biofilm (Figure 6).



Figure 6: Artificial plaque prepared with a mixture of wheat flour, water and red sustainable ink (Staedler permanent Lumocolor).

The mixture was evenly applied over the distal surface of 36 and the mesial surface of the adjacent 37. The layer applied was then left to air dry for 30 seconds to ensure adhesion and consistency. The cleaning experiment was designed to be repeatable, with standardized brushing movements in the buccolingual direction simulating typical interdental cleaning technique. All procedures were done by a professionally trained dental hygienist to ensure consistency. Each IDB was used in five buccolingual strokes, as previous studies have shown that plaque removal efficacy plateaus after five strokes (Kim, Song and Lee, 2022). The removal of the dye from the surface of the 3D-printed crowns was recorded by taking high-resolution images with a digital camera at each cycle.

2.6 Assessment of plaque removal

The cleaning efficiency of interdental brushes (IDBs) with different head shapes was evaluated by taking photographs of the embrasure before and after brushing using a digital camera (Canon EOS 250D). An area of 1.46 by 0.35 cm was chosen as a rectangle for analysis. The cleaning effectiveness was estimated using the number of pixels that were highlighted for plaque subtracted from the total number of pixels in the region of interest (ROI) that was defined and divided by the total number of pixels in the ROI and multiplied by 100 to get a percentage. The first 1.46 cm x 0.35 cm area was used as 0% cleaned for consistency because it was completely covered with artificial plaque. The amount of plaque removed in each brushing cycle was then quantified by analyzing pixel changes in the digital images using ImageJ software.

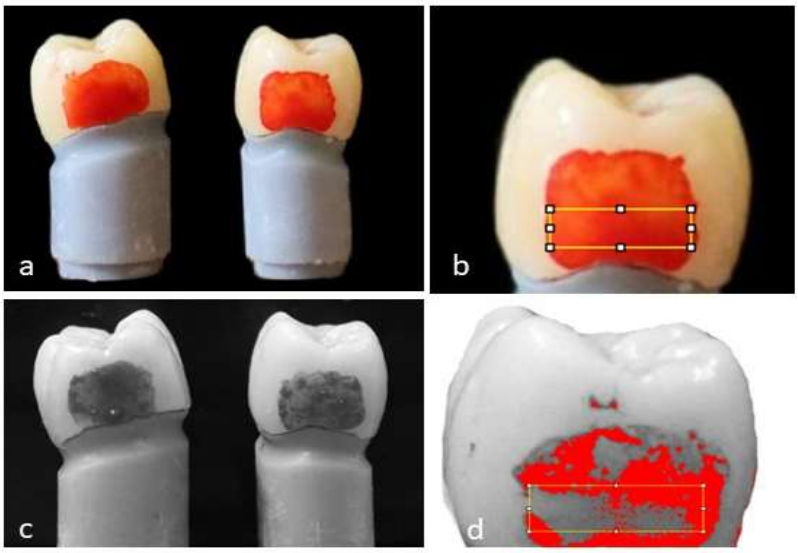


Figure 7: (a) Artificial plaque applied to the distal surface of the first molar and the mesial surface of the adjacent second molar. (b) A rectangle area of 1.46 cm x 0.35 cm was set from the bottom part of a point of contact (c) The images were converted to grayscale. (d) Images were thresholded to highlight the plaque area in red.

2.7 Statistical analysis

Intergroup comparisons among the three interdental head designs were performed using One-way analysis of variance (ANOVA) to evaluate residual plaque area and cleaning efficacy. A p-value of <0.05 was considered statistically significant.

3. Results

3.1 Residual plaque area

The trapezoidal head-shaped IDB consistently showed the lowest residual plaque area across all embrasure sizes with values 1099 at 0.7mm, 1012.5 at 0.8mm and 361.5 at 1.2 mm, while the diamond head-shaped IDB demonstrated the highest residual plaque area at each embrasure, indicating the least cleaning efficacy. (Table 1) Graphical representation of the mean Residual plaque is shown in Figure 8.

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Table 1. Intergroup comparison of Residual Plaque Area

Embrasure Size (mm)	Brush head Shape	Mean	SD	95% Confidence Interval for Mean		P value
				Lower Bound	Upper Bound	
0.7mm	Trapezoidal	1099	1.41	1086.29	1111.71	<0.001
	Diamond	2469.5	0.71	2463.15	2475.85	
	Rectangle	1950.5	13.44	1829.79	2071.21	
0.8mm	Trapezoidal	1012.5	3.54	980.73	1044.27	<0.001
	Diamond	2102.5	10.61	2007.2	2197.8	
	Rectangle	1826	33.94	1521.05	2130.95	
1.2mm	Trapezoidal	361.5	10.61	266.2	456.8	<0.001
	Diamond	1796	5.66	1745.18	1846.82	
	Rectangle	846.5	4.95	802.03	890.97	

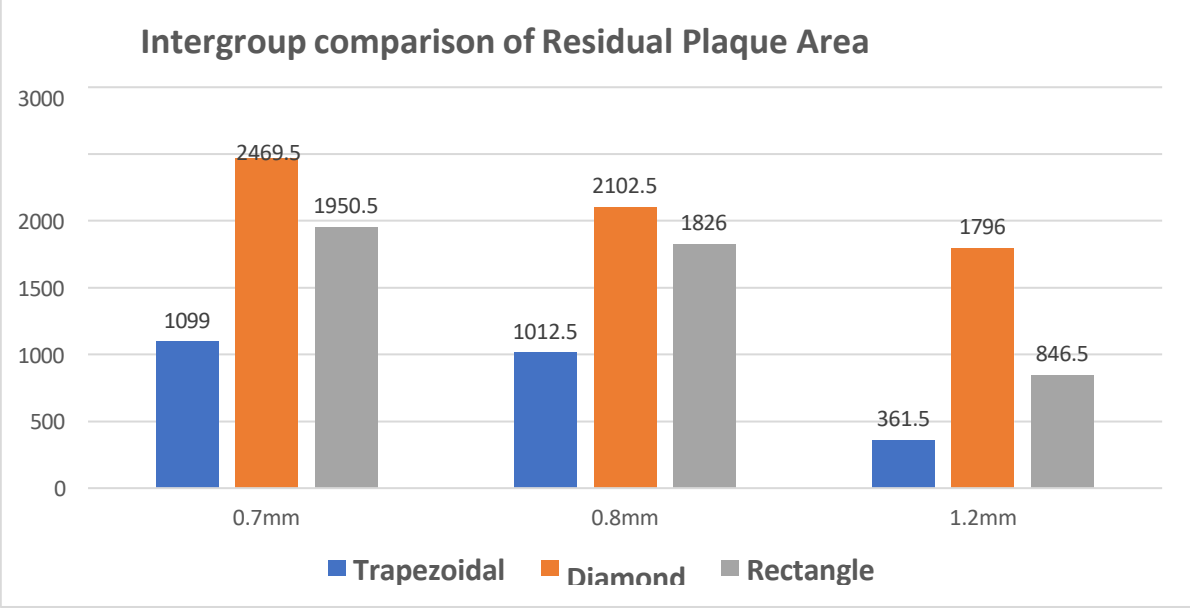


Figure 8. Graphical representation of mean Residual plaque area

3.2 Cleaning efficacy

Trapezoidal-shaped IDB achieved the highest cleaning efficacy at all embrasure sizes (78.8% at 0.7 mm, 80.6% at 0.8 mm, and 93.6% at 1.2 mm), while diamond brushes showed the lowest (51.8%, 59.5%, and 65.2%, respectively) (Table 2) Graphical representation of the mean cleaning efficacy is shown in Figure 9.

Table 2. Intergroup comparison of Cleaning Efficacy

Embrasure Size (mm)	Brush head Shape	Mean	SD	95% Confidence Interval for Mean		P value
				Lower Bound	Upper Bound	
	Trapezoidal	78.76	0.35	75.64	81.87	

0.7mm	Diamond	51.84	0.23	49.81	53.87	<0.001
	Rectangle	62.50	0.71	56.15	68.85	
0.8mm	Trapezoidal	80.62	0.54	75.72	85.51	<0.001
	Diamond	59.50	0.71	53.15	65.85	
	Rectangle	65.50	0.71	59.15	71.85	
1.2mm	Trapezoidal	93.59	0.59	88.31	98.86	<0.001
	Diamond	65.22	0.40	61.59	68.84	
	Rectangle	84.25	0.35	81.07	87.43	

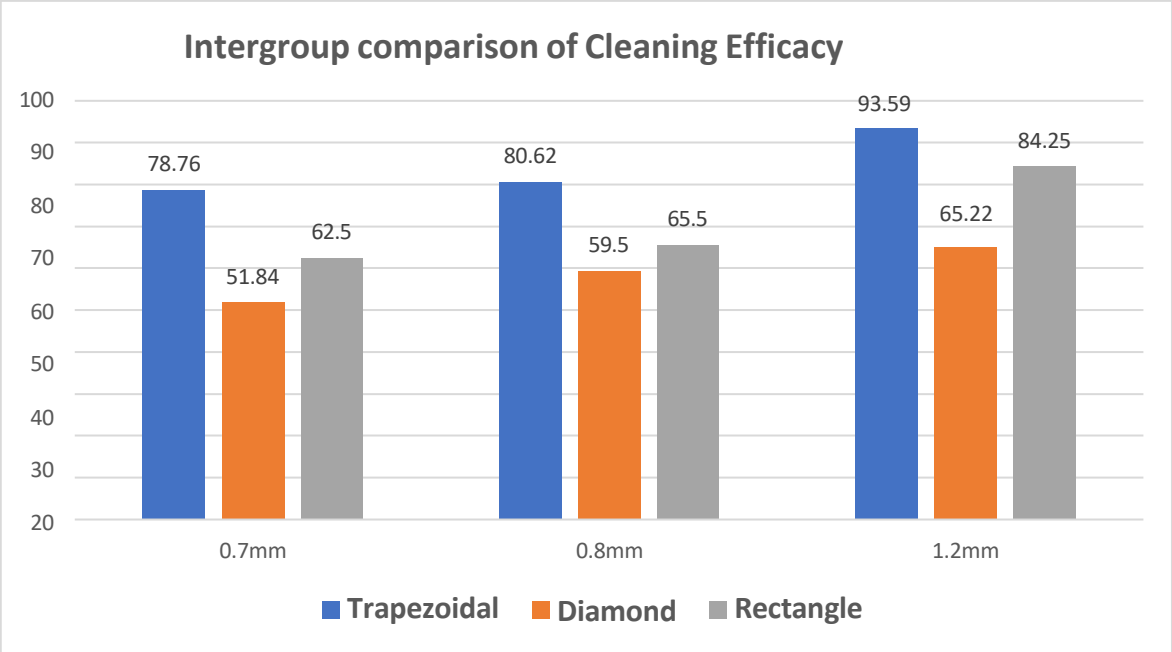


Figure 9. Graphical representation of mean cleaning efficacy

3.3 Discussion

Inadequate plaque control results in subgingival microbial recolonization within 4 to 8 weeks after non-surgical periodontal therapy; thus, meticulous interproximal hygiene is required for maintenance of periodontal health and prevention of disease recurrence (Löe, 2000; Poklepovic *et al.*, 2013; Ga *et al.*, 2018). The present in vitro study evaluated the cleaning efficacy of interdental brushes (IDBs) with trapezoidal, rectangular and diamond head shapes on 3D printed models with standardized embrasures and monolithic zirconia crowns. Zirconia crowns exhibit high durability and resistance to surface degradation during repeated cleaning cycles(Han, 2024). Data showed that the trapezoidal-shaped brushes resulted in the lowest residual plaque area and the highest percentages of cleaning efficacy across the tested embrasure sizes. Our results emphasise the importance of brush head geometry for interdental cleaning performance and are consistent with earlier studies suggesting that brush shape affects cleaning performance. A study compared waist-shaped brushes (narrowed midsection) with cylindrical ones and observed significantly better cleaning efficacy in line-angle areas for waist-shaped brushes (23.1% vs. 18.3%) (Paqué *et al.*, 2020). Similarly, in a clinical crossover study, waist-shaped IDBs produced significantly lower plaque indices than cylindrical brushes in periodontal maintenance patients ($p < 0.05$) (Schnabl *et al.*, 2020). In another study, 3D-printed crown models were prepared with embrasure sizes of 0.7 mm and 1.2 mm and tested multiple brush diameters (0.6 to 1.5 mm) in an in vitro setup. They found that a plateau of cleaning efficacy was observed after about the 5th brushing cycle for all test conditions and that the optimal diameters for 0.7 mm and 1.2 mm embrasures were 1.2 mm and 1.5 mm, respectively. (Kim, Song and Lee, 2022)

This is in accordance with our findings which suggests that slightly bigger brushes may improve penetration into concave interdental morphology (Graetz *et al.*, 2021). The positive correlation between brush diameter and cleaning efficacy has been observed in other in vitro studies where larger brushes resulted in better cleaning efficacy but at the cost of higher force which could damage the soft tissue (Wolff, Joerss and Dörfer, 2006). These studies used 3D printed tooth surfaces with geometries mimicking human interdental spaces, highlighting the growing importance of additive manufacturing in this research field. The geometry of the interdental region, such as an isosceles triangle, convex or concave embrasure can influence cleaning efficacy, suggesting that brush designs adapted to specific anatomical morphologies may provide superior cleaning performance (Erbe *et al.*, 2023). A major strength of the present study was the use of 3D-printed interdental models with standardised embrasure dimensions, incorporating zirconia crowns. This minimized inter-sample variability associated with the use of extracted human teeth, which may differ in morphology, degree of wear and surface characteristics. It also overcame the mechanical limitations of resin and acrylic models, which are susceptible to wear and deform under repeated brushing forces. The use of zirconia allowed multiple brushing cycles of repetition without substantial material degradation, thereby enhancing the reliability of the longitudinal cleaning assessments. Clinically, these findings suggest that recommendations for interdental brushes should consider not only brush diameter but also brush head geometry. In our model, trapezoidal and rectangular brush heads appear to be suited to certain embrasure geometries than diamond shaped heads. However, several limitations should be considered. As with most in vitro models, the present model cannot fully reproduce the complexity of the oral environment, including the effects of saliva, gingival tissues, individual brushing technique and biofilm dynamics. Only three embrasure sizes were evaluated; therefore, testing intermediate sizes may provide additional insights. Furthermore, the artificial plaque model differs from natural biofilm in terms of adhesion, structure and response to mechanical removal. The embrasure in the present models had uniform shapes, whereas human interdental spaces may vary in shape and contour (Wolff, Joerss and Dörfer, 2006). Further research should evaluate long-term clinical outcomes and patient-centred factors to optimize recommendations for daily oral hygiene. Future studies should also be conducted to examine the influence of brush materials, including different filament types, rubber components and coated bristles. Incorporating patient-specific interdental geometries into 3D models may further improve the clinical relevance of these investigations. Additionally, studies should assess force dynamics, thresholds for soft-tissue trauma and patient comfort associated for different brush head types.

4. CONCLUSION

Within the limitations of this in vitro study, interdental brush head shape influenced cleaning efficacy across the tested embrasure dimensions, with trapezoidal head design demonstrating superior performance followed by the rectangular and diamond head designs. These findings highlight the potential role of brush head configuration in optimizing interdental plaque removal and underscore the importance of considering brush design when selecting interdental cleaning aids.

5. LIMITATIONS

The in vitro experimental setup was unable to simulate the dynamic oral environment, such as gingival tissues and the complex characteristics of naturally occurring dental biofilm. Furthermore, the study was limited to three pre-determined interdental embrasure dimensions, which may limit the generalizability of the results to other clinical situations. Further in vivo studies are therefore warranted to validate the observed cleaning efficacy in clinical settings.

AUTHOR CONTRIBUTIONS

Dr. Mita Sarkar: Conceptualization, Investigation, Writing—Review & Editing

Dr. Supraja A: Supervision, Writing—Review & Editing.

Dr. Aparna Ganesh Kumar: Data Curation

Dr. Devi Arul: Methodology

Dr. Muthu Kumar S: Supervision

Dr. Rafi Shaik: Formal Analysis, Laboratory Analysis

FUNDING: This study was Self-funded.

CONFLICT OF INTEREST:

The authors declare that there is no conflict of interest.

ETHICS STATEMENT:

Ethical approval was obtained for this study. IEC NO: CSP/25/SEP/167/454

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