

Original Research Article

Comparative evaluation of caries removal using smart bur and ceramic bur in pediatric patients: an *in vivo* study

Muhammad Vajid C., Dhanya K. B.*, Ambili Ayilliath, Mridhul M. U.

Department of Pediatric and Preventive Dentistry, Mahe Institute of Dental Science and Hospital, Chalakkara, Palloor, Mahe, Puducherry, India

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*Correspondence:

Dr. Dhanya K. B.,

E-mail: aqualibs983@gmail.com

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ABSTRACT

Background: Minimally invasive caries removal is a key principle in pediatric dentistry that preserves healthy tooth structure, maintains pulp vitality, and enhances patient comfort. Smart burs (polymer burs) and ceramic burs are conservative excavation systems designed for selective removal of infected dentin. This study compared the efficiency, efficacy, and patient comfort associated with these two minimally invasive caries removal techniques in children.

Methods: An *in vivo* randomized split-mouth clinical trial was conducted among 26 healthy children aged 6-12 years. Two carious primary mandibular molars in each participant were randomly assigned to smart bur and ceramic bur groups. Following topical anesthesia and rubber dam isolation, caries excavation was performed using the allocated bur. Efficiency was assessed by excavation time, efficacy by visual, tactile, and caries-detecting dye assessments, and patient discomfort using the face, legs, activity, cry, and consolability (FLACC) scale.

Results: Ceramic burs demonstrated significantly greater efficiency (2.72 ± 0.26 versus 3.54 ± 0.53 min; $p < 0.0001$) and superior caries removal efficacy (0.88 ± 0.33 versus 1.92 ± 0.27 ; $p < 0.0001$). Smart burs caused no significant increase in FLACC scores ($p = 0.5$), whereas ceramic burs significantly increased patient discomfort ($p < 0.0001$).

Conclusions: Both systems were effective for minimally invasive caries removal. Ceramic burs provided superior efficiency and efficacy, while smart burs offered greater patient comfort, making them a valuable option for pediatric minimally invasive caries management.

Keywords: Smart bur, Ceramic bur, Pediatric dentistry, Minimally invasive dentistry, Caries removal, FLACC scale

INTRODUCTION

Dental caries remains one of the most prevalent chronic diseases affecting children worldwide and continues to be a major public health concern because of its adverse effects on oral health, nutrition, growth, and quality of life.¹ The World Health Organization (WHO) recognizes early childhood caries as a significant health problem requiring effective preventive and restorative strategies.²

Contemporary pediatric dentistry therefore emphasizes minimally invasive approaches that preserve tooth structure, maintain pulp vitality, and improve patient comfort.³

The philosophy of caries management has evolved from G. V. Black's concept of "extension for prevention" to minimal intervention dentistry, which advocates selective removal of infected dentin while preserving affected dentin capable of remineralization.^{4,5} This conservative approach reduces unnecessary removal of healthy tooth structure, lowers the risk of pulp exposure, and promotes long-term tooth survival, particularly in primary teeth where enamel and dentin are thinner and the pulp chamber is relatively larger.⁶

Conventional tungsten carbide and steel burs remain the most commonly used instruments for caries excavation because of their high cutting efficiency. However, their inability to distinguish infected dentin from affected dentin

may result in excessive removal of healthy tooth structure and increased risk of pulpal damage.⁷ Advances in the understanding of caries pathology have led to the development of selective caries removal techniques that preserve remineralizable dentin while effectively eliminating infected tissue.⁸

Smart burs, also known as polymer burs, were introduced as a minimally invasive alternative for selective caries removal. These burs are manufactured from polymer materials with hardness greater than infected dentin but lower than healthy dentin, allowing them to remove only softened infected dentin while becoming blunt on contact with sound dentin.^{9,10} This self-limiting mechanism minimizes over-preparation, preserves healthy tooth structure, and reduces the risk of accidental pulp exposure. Previous studies have demonstrated favorable patient acceptance and conservative cavity preparation with smart burs, although they may require longer operative time because of reduced cutting efficiency.¹¹

Ceramic burs represent another innovative approach for minimally invasive caries excavation. Manufactured from advanced ceramic materials such as zirconia or aluminum oxide, they possess excellent hardness, wear resistance, and cutting precision.¹² Ceramic burs maintain their cutting efficiency throughout the procedure, provide faster excavation, generate less heat because of their low thermal conductivity, and produce smoother cavity surfaces. These characteristics reduce the risk of thermal injury to the pulp while ensuring effective caries removal and improved clinical performance.^{13,14}

Pediatric dental treatment presents unique clinical and behavioral challenges. Primary teeth are more susceptible to pulpal injury because of their anatomical characteristics, while dental anxiety and fear often affect treatment acceptance and cooperation.¹⁵ Therefore, caries removal techniques should not only be effective but also minimize discomfort, preserve tooth structure, and facilitate positive behavior during treatment.¹⁶

Although smart burs and ceramic burs have individually demonstrated promising clinical outcomes, direct comparisons between these two minimally invasive systems are limited. Most available studies have compared each bur with conventional rotary instruments rather than with each other. Consequently, evidence regarding their relative efficiency, efficacy, and patient comfort in pediatric patients remains insufficient.¹⁷

Therefore, the present in vivo randomized clinical study was undertaken to compare smart burs and ceramic burs for caries removal in children aged 6-12 years by evaluating treatment efficiency, efficacy of caries removal, and patient discomfort. The findings of this study may contribute to evidence-based clinical decision-making and support the selection of appropriate minimally invasive caries removal techniques in pediatric dentistry.¹⁸

Aim

The aim of the study was to evaluate and compare the efficiency, efficacy and patient perception of caries removal using smart bur and ceramic bur in pediatric patients in the age group of 6-12 years.

Objectives

The objectives were to evaluate the efficiency of smart bur and ceramic bur in caries removal in children of 6-12 years, to evaluate the efficacy of smart bur and ceramic bur in caries removal in children of 6-12 years, to evaluate the patient comfort while using smart bur and ceramic bur for caries removal in children of 6-12 years, and to compare the efficiency, efficacy and patient comfort of smart bur and ceramic bur of 6-12 years.

METHODS

Inclusion criteria

Healthy children of age 6-12 years who will be willing to take part in the study, children with positive or definitely positive behaviour according to Frankel's behaviour rating scale, right and/or left maxillary and mandibular primary or permanent molars with occurrence of carious lesion into enamel and dentin on occlusal surface, and children with carious tooth without any clinical symptom with clear dentin involvement were included.

Exclusion criteria

Children with negative or definitely negative behavior according to Frankl's behaviour rating scale (1 or 2), grossly decayed and multi surface carious tooth, presence of any clinical signs and symptoms, tooth with developmental defects, and children with underlying systemic diseases and behavioural problems were excluded.

Study period

The duration of the study was from August 2025 to March 2026.

This research protocol was examined and accepted by the institutional ethics committee before conducting the study. Patients participating in the study was selected from the outpatient department of paediatrics and preventive dentistry, Mahe Institute of Dental Sciences and Hospital after obtaining written informed consent from the parents.

A total sample of 26 was calculated and was equally divided in to two groups: group 1-smart bur, and group 2-ceramic bur.

This research study was a randomized clinical trial with an allocation ratio of 1:1 randomization will be done using the lottery method. To prevent bias, two blinded examiners

were contributed, one for assigning the participants to the groups and the other one for evaluating cavity and to check whether the prepared cavities are caries free.

Statistical analysis

The collected data were organized using Microsoft Excel 2024 and analyzed using IBM statistical package for the social sciences (SPSS) statistics for Windows, version 27.0. (Armonk, NY: IBM Corp) and GraphPad Prism for windows, version 10.1.2 (GraphPad Software, La Jolla, California, USA). Normality was assessed using the Shapiro-Wilk test along with visual inspection of histograms, Q-Q plots, and box plots, which indicated that the data were skewed. Inter-rater reliability was assessed using the intraclass correlation coefficient (ICC), as the variables were continuous in nature.

Descriptive statistics were used to summarise the quantitative variables in terms of mean or median [Mdn] (as measures of central tendency), standard deviation [SD]/inter-quartile range [IQR] (as a measure of dispersion).

As the assumptions for parametric testing were not met, inferential analysis was performed using the Wilcoxon signed-rank test for both intra- and inter-group comparisons, owing to the split-mouth study design. A p value ≤ 0.05 was considered statistically significant.

RESULTS

A total of 26 children (52 teeth) aged 6-10 years participated in this split-mouth randomized clinical trial. Each participant contributed one tooth to the smart bur group (group A) and one tooth to the ceramic bur group (group B). Consequently, both groups had identical demographic characteristics. The mean age of the participants was 7.46 ± 1.14 years, with a median age of 7 years (IQR: 7-8 years). Female participants constituted 54% of the study population, while 46% were males (Table 1).

Table 1: Demographic characteristics of the study subjects.

Variables	Category	Descriptive statistics
Age (years)	Mean $\pm$ SD	7.46 ± 1.14
	Median (IQR)	7 (7-8)
	Range	6-10
Sex	Females	14 (54%)
	Males	12 (46%)

SD: standard deviation; IQR: inter-quartile range

Efficiency of caries removal

The time required for caries excavation was compared between the two study groups. The smart bur group

demonstrated a mean excavation time of 3.54 ± 0.53 minutes, whereas the ceramic bur group required 2.72 ± 0.26 minutes. The median time was 3.56 minutes (IQR: 3.52-3.81) for the smart bur group and 2.83 minutes (IQR: 2.58-2.92) for the ceramic bur group. Intergroup comparison using the Wilcoxon signed-rank test revealed that ceramic burs required significantly less time for caries removal than smart burs ($W=323$, $p<0.0001$). These findings indicate that ceramic burs were significantly more efficient for caries excavation than smart burs (Table 2).

Efficacy of caries removal

The completeness of caries removal was assessed according to the criteria proposed by Munshi et al. The smart bur group demonstrated a mean efficacy score of 1.92 ± 0.27 , whereas the ceramic bur group recorded a significantly lower mean score of 0.88 ± 0.33 . Since lower scores indicated more complete caries removal, ceramic burs exhibited superior efficacy. The median efficacy score was 2 (IQR: 2-2) for the smart bur group and 1 (IQR: 1-1) for the ceramic bur group. Wilcoxon signed-rank analysis demonstrated a highly significant difference between the two groups ($W=351$, $p<0.0001$), confirming that ceramic burs achieved more complete caries removal than smart burs (Table 3).

Inter-examiner reliability

The reliability of clinical assessments was evaluated using Cronbach's alpha and intraclass correlation coefficient (ICC). Perfect agreement was observed between the two blinded evaluators for all measured variables. Cronbach's alpha was 1.000 for efficiency, efficacy, and FLACC scores in both study groups. Similarly, the ICC for efficiency and efficacy was 1.000 (95% CI: 1.000-1.000), demonstrating excellent inter-examiner reliability and consistency of measurements.

Intragroup comparison of FLACC scores

Patient discomfort was assessed using the face, legs, activity, cry, consolability (FLACC) scale before and after caries excavation.

In the smart bur group, the mean preoperative FLACC score was 0.15 ± 0.54 , while the postoperative score was 0.00 ± 0.00 . The median score remained 0 throughout the procedure, indicating minimal discomfort. Wilcoxon signed-rank analysis showed no statistically significant difference between preoperative and postoperative FLACC scores ($W=3$, $p=0.50$), suggesting that smart bur excavation was well tolerated by the pediatric patients (Table 5).

In contrast, the ceramic bur group demonstrated a mean preoperative FLACC score of 0.54 ± 0.90 , which increased significantly to 1.92 ± 0.27 postoperatively. The median postoperative score was 2, indicating greater discomfort during the procedure. Wilcoxon signed-rank analysis

demonstrated that this increase was highly statistically significant ($W=225$, $p<0.0001$), reflecting significantly higher procedural discomfort associated with ceramic burs (Table 6).

Inter-group comparison of FLACC scores

The change in FLACC scores between the two groups was further compared. The mean difference in FLACC scores demonstrated a statistically significant difference between smart bur and ceramic bur groups ($W=270$, $p<0.0001$). Children treated with smart burs experienced significantly lower procedural discomfort than those treated with ceramic burs.

Evaluation of FLACC score distribution further supported these findings. Before treatment, 92% of children in the smart bur group and 73% in the ceramic bur group had a FLACC score of 0, indicating no discomfort. Following caries removal, all participants (100%) in the smart bur group remained pain-free with a FLACC score of 0. In

contrast, no child in the ceramic bur group recorded a postoperative FLACC score of 0; 24 children (92%) exhibited a FLACC score of 2, while the remaining 2 children (8%) recorded a score of 1, indicating significantly greater procedural discomfort.

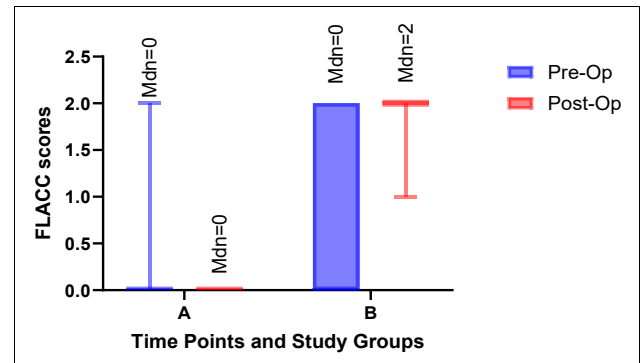


Figure 1: Median FLACC scores for the time points in group A and B.

Table 2: Inter-group comparison of the efficiency between study groups.

Study groups	N	Mean	SD	SE	95% confidence interval		Median	Q1-Q3	Minimum	Maximum	W value	P value
					Lower	Upper						
A (smart bur)	26	3.54	0.53	0.1	3.32	3.75	3.56	3.52-3.81	1.16	4.1	323	<0.0001*
B (ceramic bur)	26	2.72	0.26	0.05	2.61	2.83	2.83	2.58-2.92	2.06	2.98		

n: sample size per group; SD: standard deviation; SE: standard error of mean; Q1: first quartile; Q3: third quartile; W: statistic derived from Wilcoxon's test; *statistically significant ($p<0.05$)

Table 3: Inter-group comparison of the efficacy between study groups.

Time points	N	Mean	SD	SE	95% confidence interval		Median	Q1-Q3	Minimum	Maximum	W value	P value
					Lower	Upper						
A (smart bur)	26	1.92	0.27	0.05	1.81	2.03	2	2-2	1	2	351	<0.0001*
B (ceramic bur)	26	0.88	0.33	0.06	0.75	1.02	1	1-1	0	1		

n: sample size per group; SD: standard deviation; SE: standard error of mean; Q1: first quartile; Q3: third quartile; W: statistic derived from Wilcoxon's test; *statistically significant ($p<0.05$)

Table 4: Inter-rater reliability of FLACC scores, efficiency, and efficacy between 2 examiners.

Parameter	Group	N	Cronbach's alpha	ICC (single measures)	95% CI	Interpretation
Pre-operative FLACC	Group A	26	1.000	-	-	Perfect agreement
	Group B	26	1.000	-	-	Perfect agreement
Post-operative FLACC	Group A	26	1.000	-	-	Perfect agreement
	Group B	26	1.000	-	-	Perfect agreement
Efficiency	Group A	26	1.000	1.000	1.000-1.000	Perfect agreement
	Group B	26	1.000	1.000	1.000-1.000	Perfect agreement
Efficacy	Group A	26	1.000	1.000	1.000-1.000	Perfect agreement
	Group B	26	1.000	1.000	1.000-1.000	Perfect agreement
Overall (Combined)	Total	52	1.000	1.000	1.000-1.000	Perfect agreement

ICC: intra-class correlation coefficient; CI: confidence Intervals

Table 5: Intra-group comparison of the FLACC scores between time points in group A.

Time points	N	Mean	SD	SE	95% confidence interval		Median	Q1-Q3	Minimum	Maximum	W value	P value
					Lower	Upper						
Pre-operative	26	0.15	0.54	0.11	-0.07	0.37	0	0-0	0	2	3	0.5 (NS)
Post-operative	26	0	0	0	0	0	0	0-0	0	0		

n: sample size per group; SD: standard deviation; SE: standard error of mean; Q1: first quartile; Q3: third quartile; W: statistic derived from Wilcoxon's test; NS: not statistically significant ($p>0.05$)

Table 6: Intra-group comparison of the FLACC scores between time points in group B.

Time points	N	Mean	SD	SE	95% confidence interval		Median	Q1-Q3	Minimum	Maximum	W value	P value
					Lower	Upper						
Pre-operative	26	0.54	0.9	0.18	0.17	0.9	0	0-1.5	0	2	225	<0.0001*
Post-operative	26	1.92	0.27	0.05	1.81	2.03	2	2-2	1	2		

n: sample size per group; SD: standard deviation; SE: standard error of mean; Q1: first quartile; Q3: third quartile; W: statistic derived from Wilcoxon's test; *statistically significant ($p<0.05$)

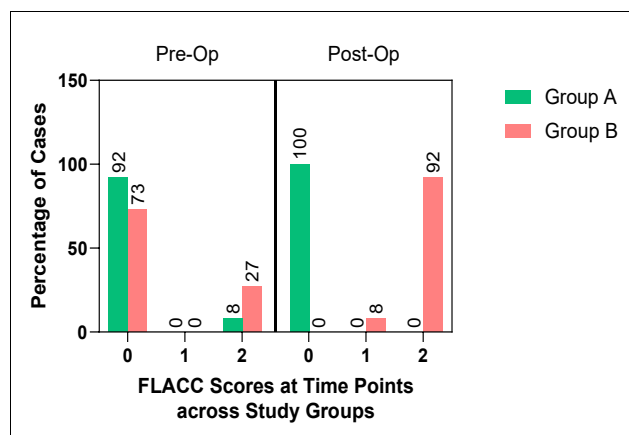
Table 7: Inter-group comparison of the difference in FLACC scores at post-operative relative to pre-operative between study groups.

Time points	N	Mean	SD	SE	95% confidence interval		Median	Q1-Q3	Minimum	Maximum	W value	P value
					Lower	Upper						
Pre-operative	26	0.15	0.54	0.11	-0.07	0.37	0	0-0	0	2	270	<0.0001*
Post-operative	26	-1.38	1.06	0.21	-1.81	-0.96	-2	-2 to -0.5	-2	1		

n: sample size per group; SD: standard deviation; SE: standard error of mean; Q1: first quartile; Q3: third quartile; W: statistic derived from Wilcoxon's test; *statistically significant ($p<0.05$)

Table 8: Distribution of FLACC scores (pre-operative and post-operative) between groups A and B.

Time point	Score	Group A, N (%)	Group B, N (%)	Total, N (%)
Pre-operative	0	24 (92)	19 (73)	43 (83)
	2	2 (8)	7 (27)	9 (17)
Post-operative	0	26 (100)	0 (0)	26 (50)
	1	0 (0)	2 (8)	2 (4)
	2	0 (0)	24 (92)	24 (46)

**Figure 2: FLACC scores (pre-operative and post-operative) between groups A and B.**

DISCUSSION

The present split-mouth randomized clinical study compared smart burs and ceramic burs for minimally invasive caries removal in children aged 6-12 years by evaluating efficiency, efficacy, and patient discomfort. The findings demonstrated that ceramic burs were significantly more efficient and achieved more complete caries removal than smart burs, whereas smart burs were associated with significantly lower procedural discomfort. These observations highlight the balance between treatment effectiveness and patient comfort that should be considered during pediatric restorative procedures.

Minimally invasive dentistry has shifted the focus of caries management from complete removal of all demineralized dentin to selective excavation of infected dentin while

preserving affected dentin capable of remineralization.¹⁹ This approach minimizes unnecessary removal of healthy tooth structure, reduces the risk of pulp exposure, and promotes long-term tooth survival, particularly in primary teeth where the pulp chamber is relatively larger and dentin thickness is reduced. Consequently, the choice of caries removal instrument has become an important determinant of both clinical success and patient acceptance.²⁰

In the present study, ceramic burs demonstrated significantly greater efficiency than smart burs, as evidenced by the shorter time required for caries excavation. The self-limiting cutting mechanism of smart burs explains their longer operating time. Polymer burs gradually lose their cutting ability after contacting healthy dentin, requiring replacement during the procedure to achieve complete excavation. In contrast, ceramic burs maintain their cutting efficiency because of their superior hardness, wear resistance, and durable cutting edges. Their ability to remove carious dentin rapidly reduces chairside time, an important advantage in pediatric dentistry where prolonged treatment may increase anxiety, fatigue, and loss of cooperation.²¹

The present finding of the study, reported that significantly longer excavation time with polymer smart burs than with ceramic or conventional carbide burs. Similar observations by Wahba et al and Shakya et al attributed the increased operating time to progressive abrasion of polymer burs during excavation.⁸ These studies, together with the present findings, indicate that although smart burs preserve tooth structure, their reduced cutting efficiency prolongs the clinical procedure.⁸

The completeness of caries removal also differed significantly between the two study groups. Ceramic burs demonstrated superior efficacy, producing significantly lower efficacy scores that indicated more complete removal of infected dentin. Their superior cutting characteristics enable effective excavation while maintaining consistent performance throughout the procedure. These findings agree with previous investigations reporting better excavation efficiency with ceramic burs than with polymer burs. Banerjee et al similarly demonstrated that ceramic burs removed infected dentin more effectively because of their greater cutting ability and resistance to wear.²²

Despite their comparatively lower efficacy, smart burs possess an important biological advantage. Their self-limiting action prevents unnecessary removal of healthy dentin and preserves affected dentin with remineralization potential. Banerjee and co-workers emphasized that selective caries removal should aim to preserve affected dentin whenever possible, thereby reducing the likelihood of pulp exposure without compromising treatment success.²² Lim et al also highlighted that complete removal of all softened dentin is not always necessary because affected dentin can remineralize after an adequate coronal seal is achieved. Therefore, although ceramic burs

demonstrated greater excavation efficacy in the present study, the conservative nature of smart burs remains consistent with the principles of minimally invasive dentistry.²³

One of the most clinically relevant findings of the present study was the significant difference in patient discomfort. Assessment using the FLACC scale demonstrated that children treated with smart burs experienced minimal discomfort throughout the procedure, whereas ceramic burs produced significantly higher pain scores. The absence of significant changes in FLACC scores within the smart bur group suggests that polymer burs provide a comfortable treatment experience. Their selective cutting action generates less pressure, vibration, and mechanical irritation, thereby reducing stimulation of dentinal tubules and pulpal tissues.⁵

Conversely, ceramic burs, despite their superior cutting efficiency, were associated with greater procedural discomfort. Their rapid cutting action and increased mechanical contact with dentin may have contributed to greater stimulation of pulpal tissues, explaining the higher postoperative FLACC scores observed in this study. Although the procedure was completed more quickly, the increased discomfort may negatively influence child cooperation and future dental acceptance.²⁴

The present findings support previous reports demonstrating improved patient comfort with minimally invasive techniques. Banerjee et al emphasized that selective caries removal systems reduce vibration, pressure, and unnecessary removal of sound tooth structure, thereby minimizing pain during treatment.²³ Similarly, Bjorndal et al reported significantly lower pain scores among children treated with smart burs than with conventional rotary instruments.^{25,26} Breschi et al also highlighted that reducing painful stimuli during dental treatment is essential for improving behavior management in children. Collectively, these studies reinforce the importance of patient-centered treatment approaches in pediatric dentistry.²⁷

Behavior management remains one of the greatest challenges in pediatric dental practice. Treatment acceptance depends not only on clinical success but also on the child's perception of pain and anxiety.⁹ Procedures associated with less discomfort improve cooperation, reduce operator stress, and create positive dental experiences that encourage future attendance. Therefore, although ceramic burs demonstrated superior efficiency and efficacy, the excellent patient comfort achieved with smart burs represents a clinically important advantage, particularly in anxious or uncooperative children.²⁸

Another strength of the present study was the excellent reproducibility of the recorded measurements. Perfect inter-examiner agreement for efficiency, efficacy, and FLACC scores confirmed the reliability of the assessment methods and minimized measurement bias. Furthermore,

the split-mouth randomized design reduced inter-individual variability by allowing each participant to serve as their own control, thereby strengthening the validity of the comparisons between the two bur systems.

Overall, the present study demonstrates that ceramic burs provide faster and more complete caries removal, whereas smart burs offer superior patient comfort during treatment. These findings indicate that neither bur system is universally superior; rather, their selection should be guided by the clinical situation and treatment objectives. Ceramic burs may be preferred when treatment efficiency and complete excavation are the primary goals, whereas smart burs may be advantageous in anxious children or deep carious lesions where preservation of healthy dentin and patient comfort are of greater importance. The results support the growing emphasis on minimally invasive, patient-centered pediatric dentistry and provide clinically relevant evidence to assist practitioners in selecting appropriate caries removal techniques.

Limitations

The study had several limitations. The small sample size of 26 children and single-center design may limit the generalizability of the findings. The study evaluated only short-term outcomes and did not assess restoration longevity, pulp vitality, or residual bacterial load. The restricted age range and selected carious lesions may limit applicability to other clinical conditions. Patient discomfort assessed using the FLACC scale may involve some subjectivity. Additionally, cost-effectiveness and other long-term clinical outcomes were not evaluated. Therefore, larger multicenter randomized clinical trials with longer follow-up are recommended to validate these findings and assess the long-term effectiveness of smart and ceramic burs.

CONCLUSION

The both smart burs and ceramic burs proved to be effective minimally invasive instruments for caries removal in pediatric patients aged 6-12 years. However, significant differences were observed in terms of efficiency, efficacy, and patient comfort. Ceramic burs demonstrated superior cutting efficiency by significantly reducing the time required for caries excavation and achieving more complete removal of infected dentin. These characteristics make ceramic burs a suitable choice in clinical situations where rapid treatment and complete caries removal are priorities, particularly in children with limited tolerance for prolonged dental procedures.

Conversely, smart burs exhibited lower cutting efficiency because of their self-limiting polymer design, resulting in a longer excavation time and comparatively less complete caries removal.²⁹ Nevertheless, this selective cutting mechanism preserved healthy and remineralizable dentin, minimized unnecessary tooth structure loss, and reduced

the risk of pulp exposure, thereby supporting the principles of minimally invasive dentistry.³⁰

A major finding of this study was the significantly lower procedural discomfort associated with smart burs, as demonstrated by the FLACC pain assessment. Their atraumatic cutting action, with reduced vibration and mechanical irritation, contributed to improved patient comfort and cooperation, which are essential for successful behavior management in pediatric dentistry. Overall, the findings suggest that the selection of a caries removal technique should be individualized according to the clinical situation, balancing treatment efficiency with preservation of tooth structure and patient comfort. Ceramic burs may be preferred when treatment speed and complete excavation are required, whereas smart burs may be advantageous for anxious or uncooperative children and in cases where conservative tissue preservation is a priority. Further multicenter studies with larger sample sizes and long-term follow-up are recommended to evaluate restoration longevity, pulp vitality, and the long-term clinical effectiveness of these minimally invasive caries removal techniques.

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