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Original Article

Effect of Diamond-like Carbon Coating Applied by the Physical Vapor Deposition Technique on Wear of Diamond and Tungsten Carbide Dental Burs

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Abstract

Background: The methods of increasing the longevity of dental burs by improving the mechanical properties of these surfaces, can increase their longevity. This study assessed the effect of diamond-like carbon (DLC) coating applied by the physical vapor deposition (PVD) technique on wear of diamond and tungsten carbide (TC) burs.

Methods: In this in vitro study, 30 diamond and 30 TC burs were evaluated in four groups, including TC burs without coating (control), TC burs with a 3.5-μm DLC coating applied by the PVD technique, diamond burs without coating (control), and diamond burs with a 3.5-μm DLC coating applied by the PVD technique. The burs were weighed by a digital scale, underwent the pin-on-disc wear test, and were weighed again. The weight loss indicated the degree of wear in each group. For qualitative assessments, the surface of the burs was inspected under a stereomicroscope at ×4 and ×10 magnifications before wear, halfway through the test, and after the test. Finally, the data were analyzed by two-way ANOVA ($\alpha=0.05$).

Results: The effect of DLC coating was significant on the wear of burs ($P=0.032$), but the effect of the type of bur and their interaction effect on wear were not significant ($P=0.151$). A significant difference existed in wear among the four groups ($P<0.001$), and the wear of coated burs was significantly lower than that of non-coated burs ($P=0.012$). Stereomicroscopic assessments revealed some residual diamond particles, the impression of dislodged particles and the path of wear on the surface of diamond burs, and the path of wear on the surface of TC burs.

Conclusions: Overall, the DLC coating of diamond and TC dental burs by the PVD technique could increase their wear resistance irrespective of the bur type.

Keywords: Diamond, Tungsten carbide, Dental burs, Physical vapor deposition

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Background

Dental burs are routinely used for sectioning and removal of hard tissues such as the tooth structure and bone. The three main components of dental burs include the body, shaft, and tip (the cutting part) (1,2). Burs are designed in different shapes and sizes and can operate at a speed of 500 000 rpm in dental hand-pieces. Dental burs are made of steel, steel, tungsten carbide (TC), pure TC, or stainless steel, and diamond particles. Due to the high hardness of TC, TC burs are highly resistant to wear. Thus, blades and the body part are often made of TC and steel, respectively. Further, the addition of 6% cobalt to TC increases its resistance. Diamond burs are composed of diamond particles attached to a metal base. Therefore, they have drawbacks such as heterogeneous size and shape of particles, difficult sterilization, and short longevity and clinical service (3-5). Dental burs have been employed in dentistry for over 300 years (5), and many attempts have been made to improve their physical properties (6).

Cutting efficiency is an important physical property for burs. However, due to the friction of the cutting edge, burs undergo wear and degradation (3). Furthermore, in the process of repeated sterilization and disinfection cycles, the superficial cutting layers corrode and become dull (7). The use of dull and corroded burs increases the pulpal temperature in dental procedures (8). Pulpal temperature rise has always been a topic of debate in dental research (9,10). In case of temperature rise > ˚5, the risk of irreversible pulpitis increases by 10%. This rate increases to over 60% in case of a temperature rise over 11˚C (11).

TC instruments are among the most commonly used cutting tools. To improve their properties and increase their longevity, TC burs are often coated with titanium nitride, titanium carbon nitride, and aluminum oxide. These coatings can be employed in one single or multiple layers. Coatings increase the wear resistance, hardness, and heat resistance of instruments, and improve the quality of tooth preparation due to lower friction and increased dimensional stability of the coated instrument. For example, aluminum oxide coating increases the wear resistance and chemical stability of instruments at high temperatures (12). Diamond coatings are also routinely applied on cutting instruments. Diamond coatings improve the function and properties of cutting instruments (13). On the other hand, although the diamond coating is a well-accepted technique, optimal coating for dental burs has not been well investigated yet (14).

Chemical vapor deposition (CVD) and physical vapor deposition (PVD) are the frequently used coating techniques, which are performed at low temperatures (15). At present, plasma-assisted CVD is considered to apply hard corrosion-resistant and wear-resistant coatings such as diamond-like carbon (DLC) on different tools (16). However, the high vapor pressure required for the CVD technique and residual graphite are the main drawbacks of this technique. Currently, the production of industrial diamonds is routinely performed, and many laboratories produce high-purity diamonds (17). The PVD technique applies titanium aluminum nitride coatings with excellent adhesion properties, along with high wear resistance. Thus, it is commonly applied to create a thermal barrier and increase wear resistance (18).

However, low ductility and poor adhesion to the underlying structure due to high residual stresses in the coating are the main limitations against the widespread use of DLC coating. Evidence suggests that the addition of elements such as silicium and chromium can obviate these limitations to some extent. Additionally, a suitable intermediate layer can be applied between the DLC coating and the underlying structure (19). At present, DLC coatings are increasingly used in medicine and dentistry. They are applied over biocompatible dental implants to ensure their optimal wear and corrosion resistance and hardness, as well as the low friction coefficient (20,21). DLC coatings are also applied over the stainless steel tip of ultrasonic instruments for bone cutting to minimize the temperature rise (22). DLC coatings are applied over nickel-titanium orthodontic wires to improve their wear and corrosion resistance. Moreover, these coatings prevent the release of nickel ions from the wires (23). They are highly efficient for cutting instruments due to their high hardness and low friction coefficient. This process can improve their wear resistance and longevity, prevent their corrosion and rusting, and enhance their function as such. It has been reported that the coating of instruments improves their quality of function by 300% (24).

Considering all the above-mentioned explanations, this study aimed to assess the effect of DLC coating applied by the PVD technique on the wear of diamond and TC dental burs.

Materials and Methods

This in vitro, experimental study was conducted on 30 diamond and 30 TC burs. The sample size was calculated to be 15 in each group assuming alpha = 0.05 and a study power of 80% (14).

The inclusion criteria were sound burs with no defects or cracks and the correct application of coating. The burs were evaluated in four groups (n = 15), including TC burs without coating (control), TC burs with a 3.5-µm DLC coating applied by the PVD technique, diamond burs without coating (control), and diamond burs with a 3.5-µm DLC coating applied by the PVD technique.

Coating Process

Diamond and TC burs were placed in an ultrasonic bath containing distilled water for cleaning and were then rinsed with acetone and ethyl alcohol (>95%). Next, they were mounted on respective fixtures on the carousel of the vacuum coating machine (Sevin Plasma, Iran) such that each bur rotated around its own central axis and the central axis of the carousel at a speed of 50 rpm and 4 rpm, respectively, and had averagely 30 cm distance from the sputtering source. The chamber was then closed and vacuumed to 3×10^{-5} mbar pressure. Vacuuming was performed in three steps by the rotary mechanical (to 5×10^{-1} mbar pressure), roots vacuum (to 5×10^{-3} mbar pressure), and diffusion (to 5×10^{-5} mbar) pumps. Then, the burs were heated to 350°C and ionized by the input of argon gas into the vacuum chamber at 20 000 V , and the pressure was adjusted at 10^{-2} mbar. Next, the burs were bumbarded with argon gas ions to eliminate the impurities from the surface. To apply the DLC coating, first, the gas input was discontinued to adjust the pressure at 3×10^{-5} mbar. Subsequently, acetylene gas in the 8:2 ratio was used to adjust the pressure at 2×10^{-2} mbar. The sputtering source of the device on which a chromium target was installed, started chromium sputtering by applying 1 kV voltage, and the Cr-DLC phase was applied on each bur. By increasing the acetylene input, the rate of Cr sputtering decreased, while the deposition of the DLC phase represented an increase. This process was continued for 120 minutes to reach the required coating thickness of 3.5 µm.

Pin-on-Disc Wear Test

First, each bur was weighed by a digital scale with 0.001 mg accuracy. Next, the burs were placed in the respective fixtures of the pin-on-disc device (Razi Institute, Iran) operating at a crosshead speed of 1.5 m/s with a 15 mm radius, 20 m distance, 954 rpm, and 500 N applied load. The distance, speed, and load were recorded in a computer, and the burs underwent wear. After the completion of the wear test, the burs were weighed again, and the difference between their primary and secondary weight was calculated and reported in milligrams (mg).

Qualitative Assessment

The burs were also inspected and photographed under a stereomicroscope (Iran) at × 4 and × 10 magnifications at baseline (before testing), halfway through the wear test, and after the completion of the test.

Statistical Analysis

Data were analyzed by SPSS, version 21. The normal distribution of data was evaluated by the Shapiro-Wilk test. Considering the normal distribution of the data ($P > 0.05$), the two-way analysis of variance (ANOVA) and Tukey's test were used for general and pairwise comparisons of the mean wear of the study groups, respectively. The level of significance was set at 0.05.

Results

Quantitative Findings

Table 1 presents the mean and standard deviation of the weight loss of burs after the wear test compared with the baseline. Two-way ANOVA results showed the significant effect of coating on wear ($P < 0.05$); however, the effect of type of bur and their interaction effect were not significant on wear ($P > 0.05$, Table 2). The pairwise comparisons of the groups regarding wear by Tukey's test demonstrated significantly lower wear of coated burs than non-coated burs ($P < 0.05$, Table 3).

Qualitative Findings

Figure 1 shows a sound diamond particle on the bur surface prior to wear at × 4 and × 10 magnifications. Figure 2 illustrates the same site of the bur surface after the wear test. As shown, all diamond particles have been detached from the surface, confirming the effects of wear on the metal surface.

Figure 3 depicts the stereomicroscopic image of the cutting tip and blades of a TC bur prior to wear at × 10 magnification. Figure 4 displays the surface of the TC bur after the completion of the test.

Discussion

This study assessed the effect of DLC coating applied by the PVD technique on the wear of diamond and TC dental burs. DLC coating is more effective than other coatings such as alumina because diamond is harder than alumina and has excellent physical and chemical properties (25). Thus, DLC coating was applied on burs by the PVD technique in the present study as described by Stoessel and Stoessel (16) to provide a hard coating, which is resistant to wear and corrosion. The thickness of the applied coating was selected to be 3.5 µm in the current study, which was similar to a study by Tuffy et al (26). They concluded that titanium nitride coating with 3.5 µm thickness had the best performance, and other thicknesses had an inferior performance due to their higher stress level, which resulted in the fracture of the coatings due to the crushing of the carbide cutting blade. However, such problems did not exist in the application

Table 1. Mean ± SD of Weight Loss of Burs After the Wear Test Compared With Baseline in Milligrams (n = 15)

Group	Mean ± SD of Wear
Carbide burs without coating	1.52 ± 6.24
Carbide burs with coating	0.31 ± 0.4
Diamond burs without coating	2.3 ± 6.7
Diamond burs with coating	0.71 ± 0.98

Note. SD: standard deviation.

Table 2. Effect of Type of Bur and Presence of Coating on Wear of Burs Using Two-Way ANOVA

Source	Sum of Squares	Degree of Freedom	Mean Square	F	*P* Value
Coefficient	774.00	1	774.00	370.66	P < 0.05
Coating	505.18	1	505.18	241.92	P < 0.05
Bur type	4.42	1	4.42	2.12	0.151
Coating × Bur type	0.02	1	0.02	0.01	0.922
Error	116.93	56	2.08		
Total	1400	60			

Note. ANOVA: Analysis of variance.

Table 3. Pairwise Comparisons of the Wear (Weight Loss) of Burs in the Four Groups by the Tukey's Test

		Compared Groups	Mean Difference	*P* Value
Tukey's test	Diamond burs without coating	TC burs without coating	0.50	0.772
		Diamond burs with coating	5.76	< 0.05
		TC burs with coating	6.34	< 0.05
	TC burs without coating	Diamond burs with coating	5.26	< 0.05
		TC burs with coating	5.84	< 0.05
	Diamond burs with coating	TC burs with coating	0.58	0.691

Note. TC: Tungsten carbide.

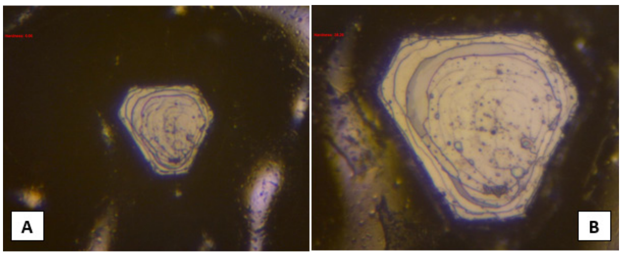

Figure 1. Stereomicroscopic Image of the Surface of a Diamond Bur at × 10 Magnification

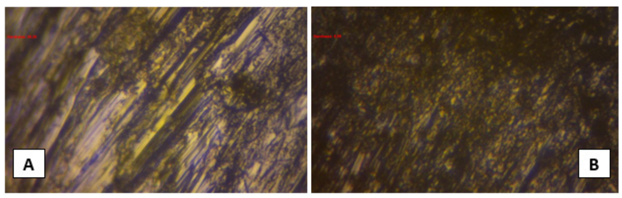

Figure 2. (**A**) Surface of a Diamond Bur Prior to the Wear Test at × 4 Magnification and (**B**) Surface of a Diamond Bur Prior to the Wear Test at × 10 Magnification

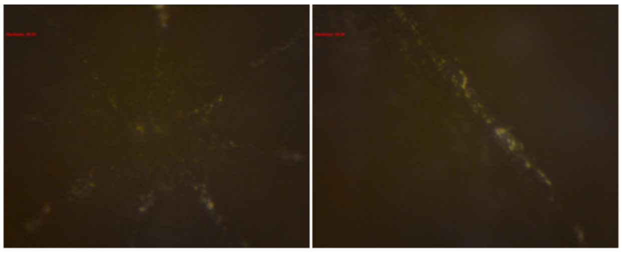

Figure 3. (**A**) Surface of a Diamond Bur After the Wear Test at × 4 Magnification and (**B**) Surface of a Diamond Bur After the Wear Test at × 10 Magnification

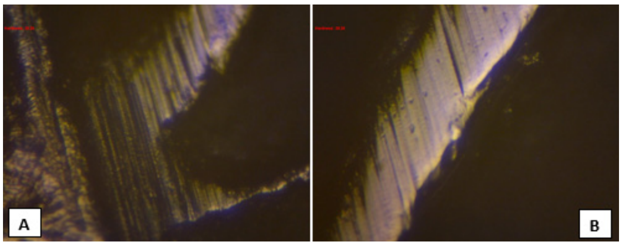

Figure 4. Stereomicroscopic Image of the Cutting Tip and Blades of a Coated Carbide Bur Prior to Wear at × 10 Magnification

of 3.5 µm coating. On the other hand, Dorner et al (27) found that DLC coatings with 0.7-3.5 µm thickness had no significant effect on the wear properties of biomedical Ti_6Al_4V alloy because microstructural differences resulted in a heterogenous DLC coating. Their results differ from the present findings probably due to the use of an abrasive device that used water pressure and different elements on the alloy surface. Qin et al (13) evaluated the effect of the thickness of diamond coating applied on the cutting instruments and reported that despite higher stresses at the interface, the instruments with thicker coatings had higher durability and longer clinical service.

The results of the present study revealed that the application of DLC coating generally improved the quality and durability of burs compared with non-coated burs, which is in agreement with the findings of Ahmed et al (5) and Qin et al (13). They found that the coating of burs prevented the reduction in the quality of the cutting blades and increased their durability. The present results are also in line with those of Borges et al (28), implying that the steriliziation process and clinical application of diamond burs resulted in a reduction in diamond particles, and subsequent reductions in the quality and clinical service of burs and hygienic contamination. They added that the coating of burs significantly decreased the detachment of diamond particles from the burs.

The current results revealed significantly lower wear of coated TC and diamond burs compared with non-coated control burs, indicating that coating significantly increased the corrosion resistance and wear resistance of burs. This result conforms to the findings of Sein et al (29), demonstrating that coating significantly increased the cutting efficiency of burs. The application of the coating on the bur surface decreased the wear of burs by 3 times, compared with non-coated burs, prevented their early wear, and improved their clinical service and function.

The present results also represented that the mean wear of diamond burs was higher than that of TC burs, which is because the main cause of wear of diamond burs is the detachment of diamond particles from the surface. However, TC burs do not have such particles, and the entire coating should be removed for the TC bur to undergo wear. This finding is in accordance with the results of Tang et al (30), highlighting that stress can cause microcracks and fracture in burs, while the coating of burs results in the generation of compressive stresses.

Stereomicroscopic assessments in the present study revealed that the diamond particles were loosely attached to the surface of diamond burs in some areas due to incorrect storage or transfer conditions, which can decrease the longevity of burs. This finding is in line with the results of Fuentes et al (31). They concluded that in non-coated burs, diamond particles are detached from the surface and decrease the longevity of burs, leading to wear of the empty space left on the bur surface and the formation of a smear layer of bur in the form of a small spot on the tooth surface. However, coating improves the resistance of burs.

The results of the current study showed that the wear of coated TC burs in the second half of the test was extremely lower than that in the first half, which is in complete agreement with the quantitative test results. This finding is due to a continuous increase in the cross-sectional area of the bur due to friction. As the cross-sectional area increases, the stress applied to the surface decreases because the surface area has an inverse correlation with the applied stress. This result corroborates the findings of Sein et al (32); they assessed the efficacy of the coating of TC burs and found that stress distribution at the tip of the bur was higher than that in other areas and caused a higher temperature rise at the tip compared with other areas. Harano et al (33) used microscopic images to assess the effect of wear on different coatings of dental burs. They reported that burs with CVD diamond coating had the highest longevity and clinical service, which is in conformity with the results of qualitative assessments in the present study.

The qualitative assessment of burs in the current study revealed the detachment of diamond particles and the impression of the path of wear on the surface of diamond burs, as well as the irregularities and impression of the wear path on the surface of carbide burs. Pournasiri et al (34) evaluated the adverse effects of sterilization cycles on diamond and TC burs. Microscopic assessments demonstrated a reduction in the number of diamond particles in diamond burs after each sterilization cycle. They also found irregularities on the surface of TC burs after repeated sterilization cycles, which is consistent with the qualitative findings of the present study. In diamond burs, friction results in the detachment of diamond particles from the surface and corrosion of the underlying metal (31). Qualitative images enable the qualitative assessment of the degradation level of diamond particles and underlying metal at each step of testing; otherwise, it cannot be found that weight loss occurs due to wear of which part of the bur.

The qualitative assessment of the surface of burs in addition to the quantitative assessment was a strength of this study. Quantitative assessment only indicates weight loss, while qualitative assessment reveals the parts that experience maximum degradation due to wear.

On the other hand, this study had some limitations. Despite its in vitro design, which limits the generalization of the results to the clinical setting, this study only assessed the effect of coating on the wear of burs. Future studies are required to investigate the effect of coating on fracture resistance, hardness, and cutting efficiency of burs. In addition, the pin-on-disc wear test was used in the present study. Future studies are needed to evaluate the adverse effects of wear of burs on enamel and dentin. Furthermore, clinical studies are required to assess the impact of the duration of the use of burs on their surface quality and optimal clinical service of coated and non-coated burs.

Conclusions

The DLC coating of the diamond and TC dental burs by the PVD technique increased their wear resistance regardless of the bur type.

Authors' Contribution

Conceptualization: Bahareh Asgartooran.
Data curation: Zahra Khamverdi.
Formal analysis: Zahra Khamverdi.
Investigation: Faezeh Soury.
Methodology: Shiva Kavousinejad, Faezeh Soury.
Project administration: Bahareh Asgartooran.
Resources: Shiva Kavousinejad.
Supervision: Zahra Khamverdi, Bahareh Asgartooran.
Validation: Zahra Khamverdi.
Visualization: Bahareh Asgartooran.
Writing – original draft: Shiva Kavousinejad.
Writing – review & editing: Shiva Kavousinejad.

Competing Interests

The authors declare that they have no conflict of interests.

Ethical Approval

The study was approved by the Ethics Committee of Hamadan University of Medical Sciences (Code: IR.UMSHA.REC.1399.237).

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