

# Improved Dental Implant Drill Durability and Performance Using Heat and Wear Resistant Protective Coatings

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The dental implant drilling procedure is an essential step for implant surgery, and frictional heat in bone during drilling is a key factor affecting the success of an implant. The aim of this study was to increase the dental implant drill lifetime and performance by using heat- and wear-resistant protective coatings to decrease the alveolar bone temperature caused by the dental implant drilling procedure. Commercially obtained stainless steel drills were coated with titanium aluminum nitride, diamond-like carbon, titanium boron nitride, and boron nitride coatings via magnetron-sputter deposition. Drilling was performed on bovine femoral cortical bone under the conditions mimicking clinical practice. Tests were performed under water-assisted cooling and under the conditions when no cooling was applied. Coated drill performances and durabilities were compared with those of three commonly used commercial drills with surfaces made from zirconia, black diamond, and stainless steel. Protective coatings with boron nitride, titanium boron nitride, and diamond-like carbon have significantly improved drill performance and durability. In particular, boron nitride-coated drills have performed within safe bone temperature limits for 50 drillings even when no cooling is applied. Titanium aluminium nitride coated drills did not show any improvement over commercially obtained stainless steel drills. Surface modification using heat- and wear-resistant coatings is an easy and highly effective way to improve implant drill performance and durability, which can improve the surgical procedure and the postsurgical healing period. The noteworthy success of different types of coatings is novel and likely to be applicable to various other medical systems.

**Key Words:** bone temperature, dental implant drill, heat generation, heat and wear resistance, protective coating, surface coating, thermocouple

## INTRODUCTION

Drilling into the bone is a critical phase of dental implant surgery. Avoiding thermally induced necrosis at the osteotomy site is crucial in preventing implant failure. If the bone temperature exceeds 47°C for more than 1 minute during the drilling process, friction between the bone and the drill can cause bone tissue necrosis.<sup>1</sup> Moreover, drills are frequently reused several times, and drills can become worn and blunt after repeated drilling and sterilization procedures.<sup>2</sup> Using worn drills to prepare osteotomies for implants generates more friction and heat, which increases the likelihood of bone necrosis, irreversible cellular damage, and the replacement of bone tissue with fat.

The aim of this study was to use hard-wearing surface coatings to improve the durability of dental implant drills and decrease alveolar bone temperature during drilling.

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## MATERIALS AND METHODS

In this study, we examined 7 different types of dental drill, each assessed using 20 drill bits:

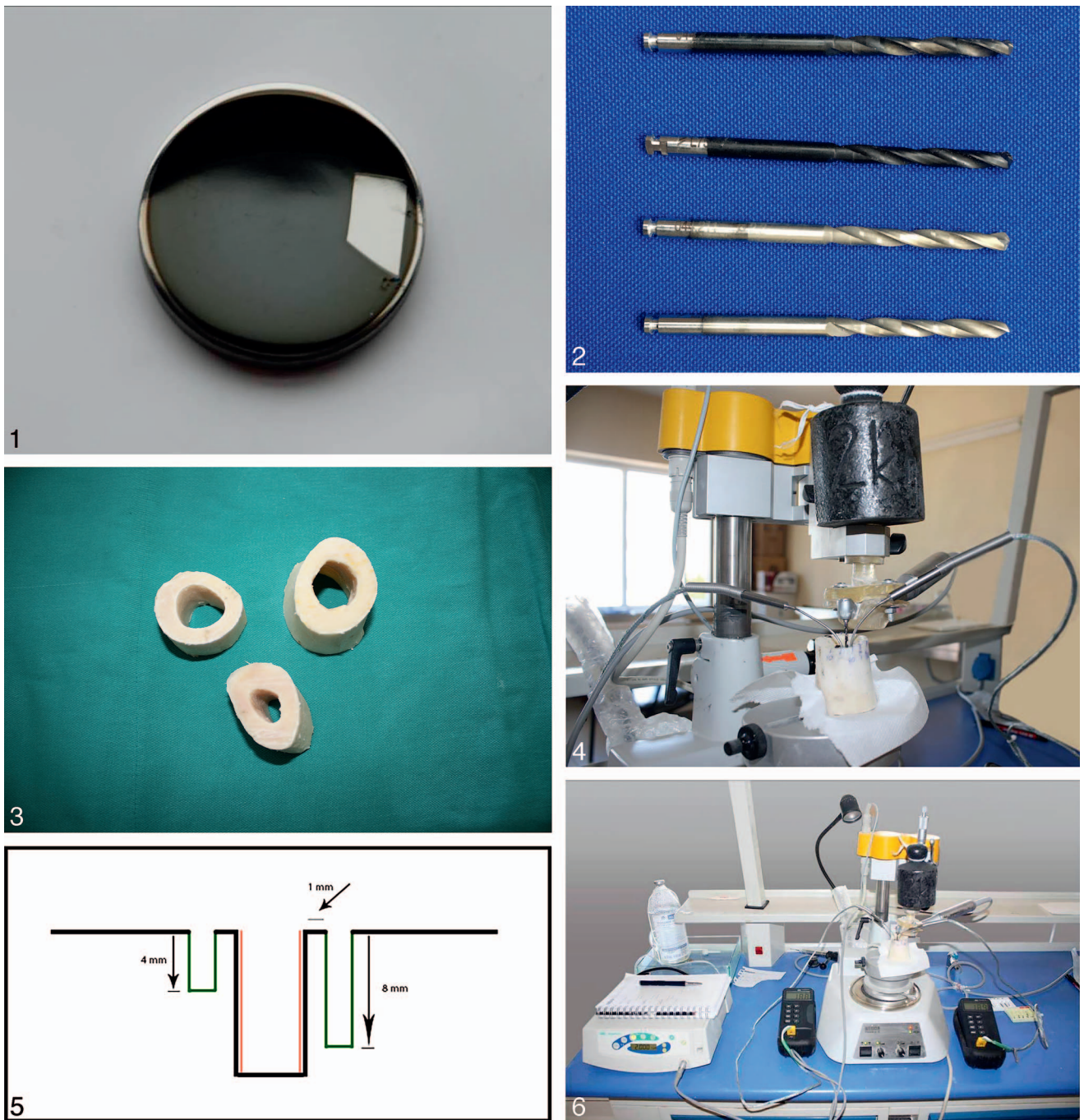
1. Titanium aluminum nitride (TiAlN)-coated drills
2. Diamond-like carbon (DLC)-coated drills
3. Titanium boron nitride (TiBN)-coated drills
4. Boron nitride (BN)-coated drills
5. Stainless steel (SS) drills
6. Black diamond (BD) drills
7. Zirconium (ZR) drills

The SS, BD, and ZR drills were commercially available drills that were tested without any surface coatings.

### Coating procedure

Commercially obtained SS dental implant drills were coated with TiAlN, DLC, TiBN, or BN using a magnetron sputter deposition system (Mantis Deposition, Ltd, Thame, UK) in the Department of Chemistry at Bilkent University, Ankara, Turkey. To optimize the coating procedure and characterize each material, the coatings were first applied to disk-shaped SS substrates (Figure 1). Each coating was then applied to the commercially available SS drills (Figure 2).

The drills were cleaned with ethanol and acetone before coating. The 99.9% pure titanium aluminum and 99.9% pure



**FIGURES 1–6.** **FIGURE 1.** Circular stainless steel substrate coated with titanium–aluminum nitride (the bright trapezoid on the right is left uncoated for the sake of characterization). **FIGURE 2.** Coated dental implant drill bits; diamond-like carbon, titanium–aluminum nitride, titanium boron nitride, and boron nitride respectively. **FIGURE 3.** Bovine femoral cortical bones. **FIGURE 4.** Image of the experimental setup with parallelometer. **FIGURE 5.** Schematic of the drilling cavity and openings for 2 thermocouples for temperature measurements. The red line is the drilling cavity and green lines are the thermocouple slots. **FIGURE 6.** Experimental setup with a contra-angle fixed to the parallelometer perpendicular to the alveolar bone, where 2 kg load is applied to the drill.

titanium boron targets were sputtered under a mixed atmosphere of nitrogen and argon to make the TiAlN- and TiBN-coated drills, respectively. The 99.9% pure BN and 99.9% pure carbon targets were sputtered under a pure argon atmosphere to make the BN- and DLC-coated drills, respectively.

### Coating characterization

The chemical properties of the coatings were determined by Raman spectroscopy, X-ray photoelectron spectroscopy, and Fourier transform infrared spectroscopy. Crystallographic characterizations were performed using X-ray diffraction spectroscopy.

copy. Hardness measurements were recorded using nano-indentation equipment.

### ***In vitro drilling procedure and bone temperature measurements***

In vitro drilling and heat measurements were performed in laboratories at the Faculty of Dentistry, Erciyes University, Kayseri, Turkey. For these tests, fresh bovine femoral cortical bones purchased from a local butcher were used because the density is similar to that of the human mandible alveolar bone (Figure 3). No animals were sacrificed for this study, as the femurs of slaughtered animals were used. The bones were stored at  $-4^{\circ}\text{C}$  and warmed to room temperature before commencing the tests. A Paraskop M parallelometer (Bego, Bremen, Germany) was used to minimize variation among tests (Figure 4). A handpiece compatible with a dental surgical motor was fixed to the parallelometer and positioned perpendicular to the bone. The drilling procedure settings were 1 minute at 2000 rpm with a load of 2 kg applied to the parallelometer (Figure 5). Bone temperatures were monitored using 2 E-RTO9-1P-04 thermocouples (Elimko Elektronik, Ankara, Turkey), each placed 1 mm from the drilling cavity. The thermocouples were positioned at depths of 4 mm and 8 mm (Figure 6). To prevent the space produced by inserting the thermocouples from interfering with heat transfer, the slots were filled with physiological saline solution. The slots were covered using a silicon-based filler to exclude any irrigation fluid, which could affect the temperature readings. Tests were performed by drilling 10 mm into the bone and then continuing drilling at this depth for 1 minute. The thermocouples displayed the maximum temperatures generated by 1 minute of drilling, even if the temperature decreased toward the end of the drilling procedure. The temperature changes were monitored, and readings recorded for the 1st, 25th, and 50th use of each dental-implant drill.

To collect data for statistical analysis, we used 20 drill bits for each type of dental implant drill. In total, 10 of the 20 drill bits were tested under water-assisted cooling conditions, and the remaining 10 were tested in the absence of a cooling system. After each test, the drills were sterilized at  $134^{\circ}\text{C}$  for 70 minutes in an autoclave to replicate standard clinical procedures.

The effects of repetitive drilling and drill sterilization cycles on bone temperatures were evaluated. The commercially available SS, BD, and ZR drills were used as controls and were subjected to identical tests.

### ***Statistical analysis***

All measurements were analyzed using SPSS (version 15.0; SPSS, Inc, Chicago, Ill) and SigmaStat software (version 3.5; Systat Software, Inc, San Jose, Calif). The normal distribution of data was assessed using the Shapiro–Wilk test. Normally distributed data are reported as mean  $\pm$  SD using descriptive statistics; nonnormally distributed data are reported as medians with the 25th and 75th percentiles. To compare two groups, independent-sample  $t$  tests and Mann-Whitney  $U$  tests were used. Kruskal-Wallis tests and one-way analyses of variance were used to compare 3 or more groups. Parametric and nonparametric

TABLE 1

Evaluations for the 4-mm and 8-mm depths in the water-assisted group; only the ZR group in the 50th drilling heat formation differed statistically significant ( $P < .05$ )\*

|   | $\bar{x} \pm ss$ |                  | Independent Samples $t$ Test ( $P$ ) |
|---|------------------|------------------|--------------------------------------|
|   | 4 mm Depth       | 8 mm Depth       |                                      |
| <b>1st drilling</b>                             |                  |                  |                                      |
| BD  | 8.36 $\pm$ 1.07  | 8.13 $\pm$ 1.30  | .691                                 |
| BN  | 2.23 $\pm$ 0.59  | 2.10 $\pm$ 0.51  | .619                                 |
| DLC   | 4.16 $\pm$ 0.57  | 4.04 $\pm$ 0.58  | .650                                 |
| SS  | 5.21 $\pm$ 0.87  | 4.75 $\pm$ 1.01  | .235                                 |
| TiALN   | 6.29 $\pm$ 0.84  | 6.46 $\pm$ 0.91  | .597                                 |
| TiBN  | 2.22 $\pm$ 0.55  | 2.13 $\pm$ 0.59  | .723                                 |
| ZR  | 9.71 $\pm$ 1.31  | 9.75 $\pm$ 0.89  | .935                                 |
| $F = 109.738; P < .001$ $F = 114.568; P < .001$ |                  |                  |                                      |
| <b>25th drilling</b>                            |                  |                  |                                      |
| BD  | 13.50 $\pm$ 1.81 | 13.73 $\pm$ 1.44 | .788                                 |
| BN  | 3.86 $\pm$ 0.72  | 3.97 $\pm$ 0.89  | .742                                 |
| DLC   | 5.84 $\pm$ 1.25  | 6.35 $\pm$ 1.11  | .311                                 |
| SS  | 8.84 $\pm$ 1.73  | 8.91 $\pm$ 2.57  | .898                                 |
| TiALN   | 8.44 $\pm$ 1.11  | 8.51 $\pm$ 1.11  | .834                                 |
| TiBN  | 4.93 $\pm$ 0.89  | 5.12 $\pm$ 0.77  | .599                                 |
| ZR  | 19.28 $\pm$ 2.47 | 19.76 $\pm$ 1.31 | .512                                 |
| $F = 121.928; P < .001$ $F = 148.002; P < .001$ |                  |                  |                                      |
| <b>50th drilling</b>                            |                  |                  |                                      |
| BD  | 26.39 $\pm$ 4.47 | 26.83 $\pm$ 2.08 | .585                                 |
| BN  | 4.47 $\pm$ 1.21  | 4.99 $\pm$ 1.00  | .188                                 |
| DLC   | 8.03 $\pm$ 0.95  | 8.34 $\pm$ 1.08  | .438                                 |
| SS  | 11.56 $\pm$ 1.60 | 11.07 $\pm$ 1.97 | .174                                 |
| TiALN   | 10.90 $\pm$ 1.54 | 11.5 $\pm$ 1.61  | .124                                 |
| TiBN  | 7.27 $\pm$ 1.91  | 8.72 $\pm$ 1.74  | .176                                 |
| ZR  | 23.83 $\pm$ 3.94 | 25.50 $\pm$ 2.41 | .044                                 |
| $F = 149.381; P < .001$ $F = 207.235; P < .001$ |                  |                  |                                      |

\*BD indicates black diamond; BN, boron nitride; DLC, diamond-like carbon; SS, stainless steel; TiALN, titanium–aluminum nitride; TiBN, titanium boron nitride; ZR, zirconium.

Student-Newman-Keuls tests were used for multiple comparisons. A  $P$  value  $< .05$  was considered statistically significant.

## **RESULTS**

### ***Temperature differences at 4- and 8-mm depths***

Table 1 shows the data for intragroup comparisons among the water-assisted cooling tests. Only the 50th test repeats in the ZR-drill group showed significantly different frictional heat at 4 mm that at 8 mm, with more heat being generated at a depth of 8 mm ( $P < .05$ ).

The data for intragroup comparisons among the tests with no cooling system are shown in Table 2. The heat produced at 4 mm and 8 mm differed significantly in the BD- and ZR-drill groups for the 1st, 25th, and 50th test repeats. A significant difference in the heat produced at 4 mm compared with 8 mm in the TiBN-drill group during the 25th test repeat was also observed ( $P < .05$ ).

### ***Effect of water-assisted cooling***

Comparing the water-assisted cooling with uncooled drilling tests demonstrated that in the first test repeat, the heat

TABLE 2

In noncooling experiments BD and ZR in the 1st, 25th, and 50th drilling and TiBN in the 25th drilling showed statistically significant results at different depths\*

|                      | Median (25th to 75th Percentile)    |                                     | Mann-Whitney U Test (P) |
|----------------------|-------------------------------------|-------------------------------------|-------------------------|
|                      | 4 mm Depth                          | 8 mm Depth                          |                         |
| <b>1st drilling</b>  |                                     |                                     |                         |
| BD                   | 21.80 (20.10–25.80)                 | 35.30 (34.40–38.00)                 | .005                    |
| BN                   | 2.50 (2.00–3.10)                    | 2.55 (2.20–2.60)                    | .888                    |
| DLC                  | 12.00 (11.80–12.60)                 | 12,45 (11.60–12.70)                 | .799                    |
| SS                   | 20.75 (19.40–23.40)                 | 20.10 (18.10–21.20)                 | .332                    |
| TiALN                | 26.35 (25.70–27.30)                 | 25.45 (24.20–26.20)                 | .051                    |
| TiBN                 | 2.70 (2.00–3.60)                    | 1.90 (1.50–3.50)                    | .154                    |
| ZR                   | 39.60 (36.70–40.20)                 | 35.70 (34.80–37.30)                 | .005                    |
|                      | <i>H</i> = 63.802; <i>P</i> < .001  | <i>H</i> = 64.826; <i>P</i> < .001  |                         |
| <b>25th drilling</b> |                                     |                                     |                         |
| BD                   | 23.50 (21.70–30.20)                 | 44.50 (40.60–46.90)                 | .005                    |
| BN                   | 7.50 (6.40–8.50)                    | 6.70 (6.00–8.70)                    | .594                    |
| DLC                  | 17.80 (15.20–20.00)                 | 17.70 (15.60–21.60)                 | .092                    |
| SS                   | 23.65 (21.80–25.00)                 | 22.80 (20.90–25.00)                 | .441                    |
| TiALN                | 27.30 (22.90–30.80)                 | 28.55 (27.00–30.50)                 | .508                    |
| TiBN                 | 12.00 (11.80–12.50)                 | 13.20 (11.70–13.80)                 | .032                    |
| ZR                   | 44.90 (42.70–46.40)                 | 41.60 (39.90–43.80)                 | .005                    |
|                      | <i>H</i> = 60.671; <i>P</i> < .001  | <i>H</i> = 64.569; <i>P</i> < .001  |                         |
| <b>50th drilling</b> |                                     |                                     |                         |
| BD                   | 26.39 ± 4.47                        | 26.83 ± 2.08                        | .585                    |
| BN                   | 4.47 ± 1.21                         | 4.99 ± 1.00                         | .188                    |
| DLC                  | 8.03 ± 0.95                         | 8.34 ± 1.08                         | .438                    |
| SS                   | 11.56 ± 1.60                        | 11.07 ± 1.97                        | .174                    |
| TiALN                | 10.90 ± 1.54                        | 11.5 ± 1.61                         | .124                    |
| TiBN                 | 7.27 ± 1.91                         | 8.72 ± 1.74                         | .176                    |
| ZR                   | 23.83 ± 3.94                        | 25.50 ± 2.41                        | .044                    |
|                      | <i>F</i> = 149.381; <i>P</i> < .001 | <i>F</i> = 207.235; <i>P</i> < .001 |                         |

\*BD indicates black diamond; BN, boron nitride; DLC, diamond-like carbon; SS, stainless steel; TiALN, titanium–aluminum nitride; TiBN, titanium boron nitride; ZR, zirconium.

TABLE 3

Comparison of water-assisted and noncooling method; only in the BN and TiBN groups at the 4-mm and 8-mm depths in first drilling there was no difference (*P* > .05)\*

|                   | Median (25th to 75th Percentile) |                  | Mann-Whitney U Test (P) |
|-------------------|----------------------------------|------------------|-------------------------|
|                   | Water-Assisted                   | Noncooled        |                         |
| <b>BN</b>         |                                  |                  |                         |
| 4 mm 1st drilling | 2.10 (1.88–2.75)                 | 2.51 (1.98–3.13) | .324                    |
| 8 mm 1st drilling | 2.05 (1.68–2.35)                 | 2.50 (2.18–2.70) | .404                    |
| <b>TiBN</b>       |                                  |                  |                         |
| 4 mm 1st drilling | 2.30 (1.93–2.65)                 | 2.64 (1.90–3.60) | .909                    |
| 8 mm 1st drilling | 2.20 (1.90–2.43)                 | 2.38 (1.50–3.53) | .288                    |

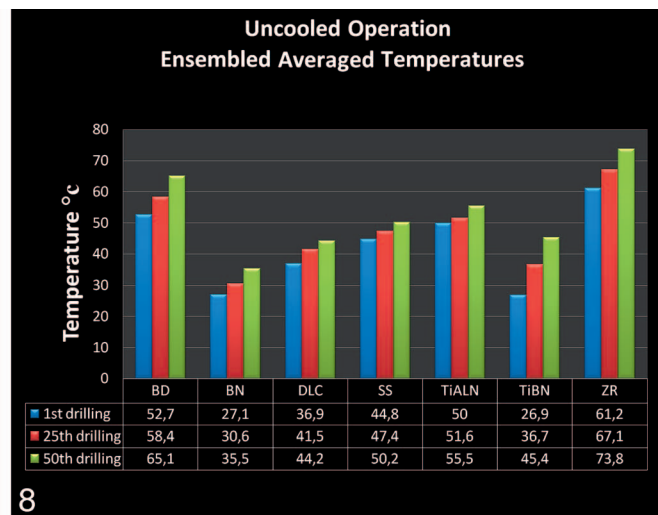
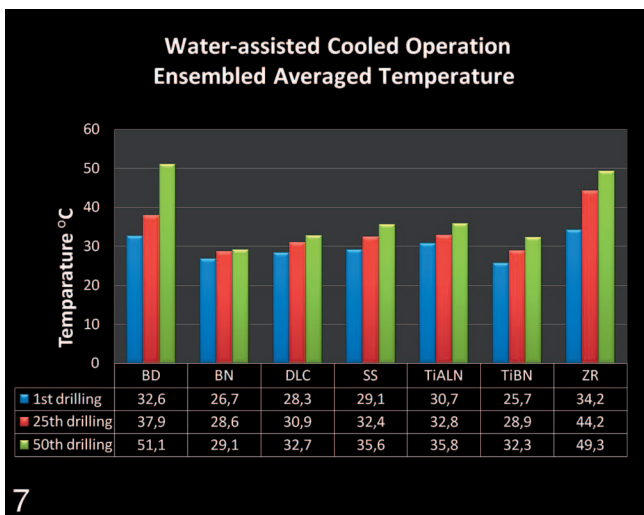
\*BN indicates boron nitride; TiBN, titanium boron nitride.

produced by the BN- and TiBN-drill groups did not differ significantly at the 4-mm depth compared with the 8-mm depth (*P* > .05). All other group comparisons showed that less frictional heat was produced with water-assisted cooling (Table 3).

**Mean temperatures**

The mean bone temperatures under the water-assisted cooling condition are shown in Figure 7, where the basal temperature was 23°C to 24°C. Compared with bare SS drill bits, the BN-, TiBN-, and DLC-coated drills showed significant improvements in drill-bit longevity and bone temperature, whereas the performance of TiALN-coated drill bits showed no improvements. The BN-coated drill bits displayed the best performance, with the bone temperature not exceeding 29.1°C even after the 50th test.

Similar results were observed for the uncooled drilling procedures (Figure 8). In these tests also, the BN-coated drill bits displayed the best performance, with the bone temperature not exceeding 35.5°C even after the 50th test. In the absence of external cooling, the use of DLC- and TiBN-coated dental implant drills would not be feasible. As we demonstrated in the water-assisted cooling tests, the TiALN coatings had



FIGURES 7 AND 8. FIGURE 7. Mean bone temperature values obtained during drilling procedure with water-assisted cooling recorded for 50 drillings. FIGURE 8. Mean bone temperature values obtained during drilling procedure without any cooling recorded for 50 drillings.

no effect on the performance or durability of SS drill bits. In contrast, BN-, TiBN-, and DLC-coated drill bits were highly effective, even under uncooled conditions.

### Discussion

Osseointegration is defined as the direct structural and functional connection between ordered living bone and the surface of a load-carrying implant.<sup>3</sup> Heat generation during rotary cutting is one of the most important factors influencing osseointegration<sup>4</sup> because heat-induced tissue injuries reduce the initial stability of the implant, leading to implant failure.<sup>5,6</sup> If the bone is exposed to temperatures exceeding 47°C for more than 1 minutes during drilling, irreversible cellular damage will occur, and bone tissue will be replaced with fat.<sup>1,7</sup>

Previous investigations into heat generation while drilling osteotomies for dental implants have used a variety of materials, including rabbit mandibles,<sup>8</sup> pig maxillae and mandibles,<sup>9</sup> bovine block cortical/medullary bone,<sup>10</sup> and bovine cortical bone.<sup>2,11,12</sup> Many studies have indicated that bovine bone and human mandibular bone have similar densities and cortical and cancellous bone structures.<sup>2,10,13,14</sup> Additionally, because similar structural morphology indicates similar thermal conductivity, bovine bone is a preferred material for temperature measurement studies.<sup>15</sup> Our study also used bovine femoral cortical bone to minimize variability, ensure uniform cortical thickness, and generate results that were comparable to those of similar investigations.

Coating materials is a well-known procedure for improving surface characteristics, and friction-resistant surface coatings are of particular interest because of the need to protect materials in abrasive environments. Metal nitride coatings perform especially well as surface protectants. The magnetron sputtering technique has become the method of choice for depositing a wide range of industrially important coatings, including wear-resistant, low-friction, corrosion-resistant, and decorative coatings.<sup>16</sup> It is particularly useful for applying tough coatings to materials with sharp cutting edges.<sup>17</sup> We chose the magnetron sputtering method to ensure good adhesion of high-quality homogenous coatings to the drill surfaces.

Aisenberg and Chabot first described the abrasion- and corrosion-resistant properties of DLC.<sup>18</sup> Because of their excellent tribologic properties, including low friction coefficients, increased hardness, durability, and biocompatibility, DLC protective surface coatings are widely used in many industrial and medical applications.<sup>19,20</sup> In our study, we demonstrated that DLC-coated dental implant drills displayed an approximately 20% improvement in performance and durability compared with bare SS drills and could be used for up to 20 drilling procedures without water-assisted cooling. Therefore, DLC is a good surface coating for dental implant drills.

In addition, TiAlN coatings are widely used as protective coatings in industrial applications because of their good mechanical properties, such as hardness, durability,<sup>18-21</sup> resistance to corrosion,<sup>22</sup> and high-temperature-induced oxidation.<sup>23</sup> However, we observed no significant improvement in the performance of TiAlN-coated compared with bare SS implant drills in either cooled or uncooled drilling procedures. This could be due to the low thermal conductivity of TiAlN,<sup>24</sup>

which would result in the retention of heat at the bone surface. This, in turn, would increase the longevity of the cutting tool, but any heat generated would be trapped at the tool's surface, making TiAlN coatings unsuitable for dental implant drills. Infrared thermography could be used to test this hypothesis.

Surface coatings containing boron are not yet widely used in industry but are of interest to the scientific community because of their hardness and resistance to abrasion. The minimal use of boron-containing surface coatings in the medical tools industry may be due to the fact that the characterization and optimization of these coatings are still at an early stage. An optimized composition of TiBN films demonstrated that this had at least 3 times as much abrasion resistance as titanium nitride and hardness values of more than 50 GPa.<sup>25</sup> Additionally, cubic BN is the hardest form of BN and is almost as hard as diamond. Its strong resistance to corrosion and very low friction coefficient mean that BN has great potential as a protective surface coating.<sup>26</sup> Additionally, the thermal conductivity values of TiBN and BN were higher than those of the other coatings we examined. This prevents heat from being trapped at the bone surface and reduces bone temperature. As a result, we found that the BN and TiBN coatings performed best in our study. The performance of the BN-coated dental drills was particularly outstanding because the bone temperature remained well below the necrosis limit of 35.5°C, even after the 50th test under uncooled conditions. Additionally, the BN-coated drill bits produced gradual increases in bone temperature through the 1st (27.1°C), 25th (30.6°C), and 50th (35.5°C) tests, suggesting that the drill has long-term durability.

During drilling, bone temperatures can be measured directly using thermocouples or indirectly using infrared thermography.<sup>27</sup> Although infrared thermography is a sensitive and reliable method for measuring temperature changes, the temperature of an irrigation solution would mask the true temperatures.<sup>28</sup> Additionally, infrared thermography equipment is expensive and can only be used to estimate superficial temperatures over large areas. Thermocouples are more commonly used to measure heat generation during bone surgery,<sup>28,29</sup> and they display the maximum bone temperature reached during a procedure. We used drilling times of 1 minute to standardize the drilling parameters. According to Eriksson and Albrektsson, "if the bone temperature exceeds 47°C for a duration of approximately 1 min or longer, there is a risk of bone tissue necrosis."<sup>30</sup> Another reason for using thermocouples to measure bone temperatures was that this enabled us to compare our results directly with those from many previous studies.

Previous investigations have reported different approaches to addressing the problem of excessive heat production during bone drilling procedures. For example, Chacon et al<sup>11</sup> evaluated the effect of dental implant drill geometry on heat production. These authors showed that bone temperatures increased when drill bits were used multiple times, and concluded that drill geometry played a major role in heat production. Oh et al<sup>31</sup>

also examined the effects of implant drill design and the drill-bone contact area on heat production and revealed that a decrease in the contact area between the drill and bone reduced heat production. Scarano et al<sup>12</sup> compared the

amount of heat generated by cylindrical and conical drills using bovine femoral cortical bone and showed that both drill geometry and the number of flutes are important factors in heat production during implant site preparation. Different drills are designed to have greater cutting surface areas by changing the positions and angles of drill grooves. The geometry of the drill determines its contact area, and this, in turn, influences bone surface temperatures. In our study, only the BD drill had a different geometric structure, which may be why it generated more heat than the other drills. In particular, the temperature differences observed between depths of 4 mm and 8 mm under uncooled conditions may be related to the different BD drill design.

Sterilization procedures performed under high temperature and pressure can also affect the cutting efficiency of drills by producing abrasions and corrosion.<sup>32</sup> Sterilizing a dental implant drill in an autoclave can decrease the efficiency of drill rotation, reduce its cutting power, and produce corrosion.<sup>29,32</sup> The bone drilling procedures, repeated use of drills, and sterilization procedures all have negative impacts on dental implant drill longevity and long-term performance. In our study, we sterilized the drills after each test to simulate procedures used in clinical practice and evaluate the effect of sterilization cycles.

Few previous studies have focused on the effects of drill-surface properties and durability on heat production during implant site preparation. An *in vitro* study by Oliveira et al<sup>34</sup> examined the effects of twisted SS and Zr-based ceramic drills on thermal changes in bovine bone tissue during implant site preparation and revealed that ceramic drills produced less heat after 50 implant site preparations. Scanning electron microscope (SEM) images showed some signs of wear in both drills after 50 procedures; however, the study did not examine the effects of sterilization procedures. A similar study by Mendes et al<sup>33</sup> showed no significant differences in mass for DLC-coated, ZR, and smooth SS drills after 40 drilling and sterilization procedures. The ZR drill surfaces remained regular, whereas the SS drills revealed signs of wear. In contrast, our study examined the effects of wear on heat production and found that the ZR drills produced more heat than the SS drills.

Koo et al<sup>35</sup> compared titanium nitride-, tungsten carbide-, and ZR-coated drills and concluded that irrigation may be more important than drill material for controlling bone temperatures. They also recommended that drills not be used to create more than 50 osteotomies. The importance of irrigation is also clear from our study; however, in contrast to Koo et al,<sup>35</sup> our results demonstrated that drill material is an important factor in increasing drill longevity and performance.

Ercoli et al<sup>2</sup> also evaluated the cutting efficiency, durability, heat generation, and wear of seven commercially available implant-drill brands used in 100 successive osteotomies. Their study involved a total of 7 groups, including 2 with a titanium nitride coating. The authors concluded that the bit design, material, and mechanical properties of the drill all significantly affect cutting efficiency and durability. They also concluded that drills could be used up to 100 times and bone temperature would remain below 47°C when external cooling was applied. However, these drills were cleaned using water, and no sterilization procedures were investigated. In contrast, our

results showed that after 50 cycles of repeated use and sterilization, the SS drills produced bone temperatures of up to 47°C. Therefore, we do not recommend using bare SS drill bits more than 50 times, even with water-assisted cooling.

One of the problems that can occur with novel drill coatings is poor adhesion, resulting in delamination, that is, loss of the coating from the drill surface.<sup>36</sup> Delamination reduces a material's structural integrity and leads to poor assembly tolerance and long-term deterioration in performance.<sup>37</sup> It can also release particles into the osteotomy, affecting postoperative healing time.<sup>38</sup> Fritsche et al<sup>39</sup> stated that delamination of the coating during implantation must be avoided because material component may lead to adverse response in bone tissue, resulting in aseptic implant failure. Possible mechanism may be the development of inflammation or necrosis in the implant-surrounding tissues caused by physical and chemical effects of the delaminated material components influencing pathobiology of the host.<sup>40</sup> In several autopsy reports, small amounts of fibrous tissue were found between well-fixed implants and surrounding bone, whereas a thick fibrous pseudomembrane that contains numerous implant-derived wear particles that induce immune response lymphocyte reaction and foreign body macrophage were found between the bone and loose implants.<sup>41</sup> Delamination-related infection and septic implant loss may also develop. Although drilling is performed under irrigation in clinical practice, particles from the drill may remain in the cavity. This can lead to postoperative infection or interfere with the engagement of screws and bone adjacent to the osteotomy, leading to misalignment of the implant.<sup>38,42</sup> In light of these findings, one reason for the popularity of biological implant coatings is that they may prevent infections and inflammation. In our study, delamination tests were performed before coating drill surfaces, but further delamination tests will be required before these coatings are commercialized.

The limitations of this study include the lack of SEM images and evaluation of drill abrasion using only bone temperature after 50 tests. The SEM analyses use comparative images that display irregularities, abrasions, and delamination of drill surfaces before and after sterilization and drilling procedures. Batista Mendes et al,<sup>32</sup> Oliveira et al,<sup>34</sup> Bayerlein et al,<sup>43</sup> and Scarano<sup>13</sup> all used SEM images to assess the relationship between heat formation and drill abrasion; however, these studies were based on a small number of drilling procedures. Our study investigated the development of novel surface coatings that minimized differences in bone temperature between water-assisted cooling and uncooled procedures, and we used a large number of drilling procedures to provide data that could be analyzed statistically. However, there is a need for further studies that investigate our results using SEM images from smaller sample groups.

## CONCLUSIONS

In conclusion, surface modification using hard, wear-resistant coatings is a highly effective way to enhance dental implant drill longevity and to decrease alveolar bone temperature during drilling procedures. This study successfully generated novel surface coatings that improved the performance of

dental implant drills by minimizing increases in bone temperature. Further studies with fewer experimental groups should include SEM images to evaluate damage to the surfaces of the newly developed drills.

#### ABBREVIATIONS

BD: black diamond  
 BN: boron nitride  
 DLC: diamond-like carbon  
 SEM: scanning electron microscope  
 SS: stainless steel  
 TiAlN: titanium aluminum nitride  
 TiBN: titanium boron nitride  
 ZR: zirconium

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#### NOTE

The authors deny any conflict of interest related to this study

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