

Comparison of wear and temperature of zirconia and tungsten carbide tools in drilling bone: in vitro and finite element analysis

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Abstract

Drilling is extensively used in operations on bones and dental implants, and yet poses a considerable challenge because it can damage cells as well as cause mechanical and thermal stresses to the bone. The goal of this study was to assess the temperature changes and instrument wear using both zirconium dioxide (ZrO₂) ceramics and tungsten carbide (WC) tools using a 3-dimensional finite element analysis (FEA) of bone drilling. The wear of conical burrs made from ZrO₂ and tungsten carbide was measured using scanning electron microscopy (SEM) and image processing software. Temperature was measured by an infrared thermometer. As well as 3-dimensional FEA, the temperature and wear of the burrs was predicted with the aid of the Johnson-Cook model for bone material properties. Comparison between the ZrO₂ and WC burrs using SEM showed that the ZrO₂ burr was less worn than the WC burr ($p=0.044$) and there was significant difference in temperature between the two ($p=0.020$). We conclude that ZrO₂ tools are a suitable alternative to WC, particularly in superficial drilling with coolant, as they wear less than the WC tools. The results of the FEA successfully predicted the variation in temperature and the wear on the tools.

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Keywords: Bone drilling; Finite Element Analysis; Tool wear; Scanning Electron Microscopy; Ceramic tool

Introduction

One of the important factors in patients' health is the integrity of the surface of the bone after osteotomy, which can pose some difficulties during an operation. Among the most important challenges are possible rises in temperature,^{1,2} necrosis of the bone, and unfavourable mechanical pressure (which alone can easily lead to mechanical fracture). These effects can all damage or harm living cells and organs.³

Depending on the amount of the heat produced, bones may develop hyperaemia, necrosis, fibrosis, or increased osteoclast activity during the osteotomy.^{4,5} Variables that affect the temperature during bone drilling can be divided into three categories: characteristics and geometry of instruments,⁴ characteristics of bone,² and operational conditions such as speed, cooling conditions, and pressure.⁶

An uncontrolled osteotomy in oral surgery could provoke bony damage. In particular, in the field of implantology it is important to pay attention during preparation of the bone. By decreasing damage during the osteotomy the surgeon can increase the success rate of the implant, and some studies have been reported about the design and cutting properties. For example, the stability of different designs of drill was investigated by Gehrke et al.⁷

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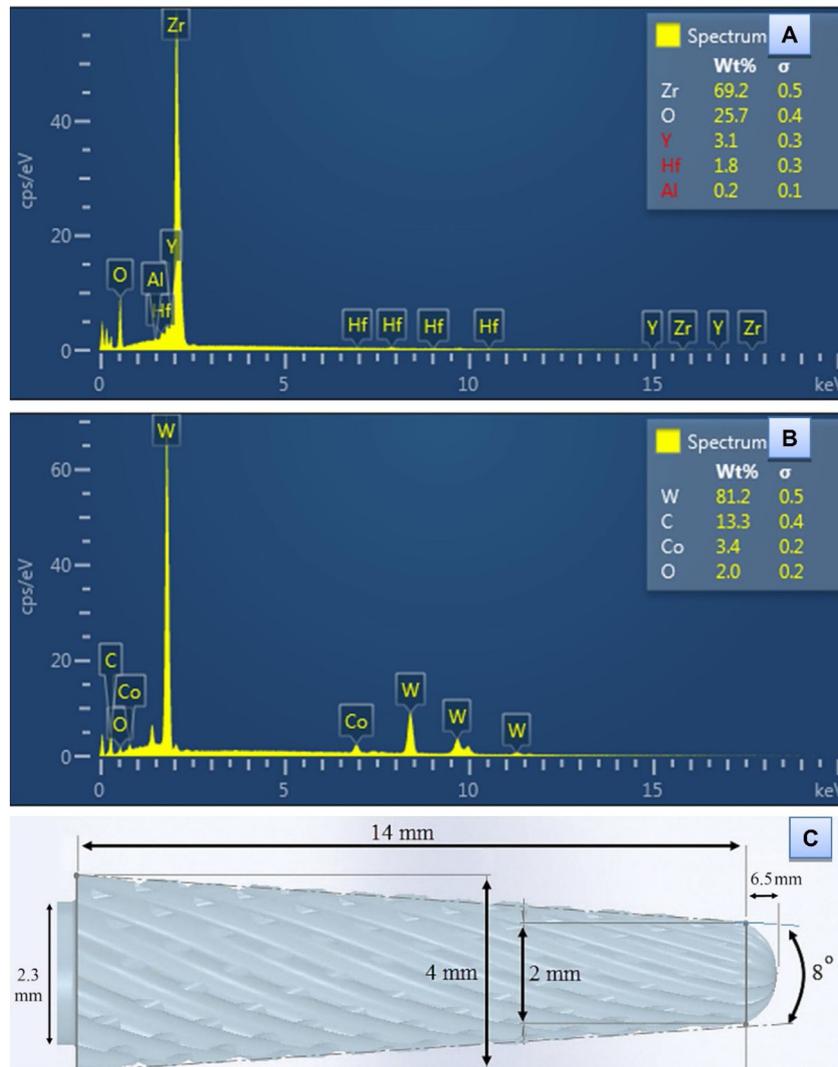


Fig. 1. (A) Energy-dispersive X-ray spectroscopy (EDAX) analysis of the zirconium oxide (ZrO_2) tool. (B) EDAX analysis of the tungsten carbide (WC) tool. (C) Geometry of burrs used.

One of the most important challenges in bone drilling has to do with temperature.³ Many factors influence the temperature during drilling such as the properties of the tool,⁴ the properties of bone,² and the type of operation.⁶ Investigations have reported that temperatures of over 44 °C lead to irreversible damage. One of the causes of the rise in temperature during drilling is the amount of wear on the tool, which needs to be controlled to avoid thermal osteonecrosis.⁸

The purpose of this study was to examine the wear and temperature changes of two conical tools made from zirconium dioxide (ZrO_2) and tungsten carbide (WC) in vitro and by 3-dimensional finite element analysis (FEA).

Material and methods

Experimental technique

Two conical burrs with different material properties (ZrO_2 and WC) were used. These were analysed chemically using

energy-dispersive X-ray spectroscopy (EDAX) (Fig. 1A and B).

The WC tool has 10 cutting edges and the ZrO_2 tool 16. For both of them the cutting edge angle was 60°, the rake angle 20°, and helix angle 25° (Wilson Precision Tool, Inc). The geometrical dimensions of the burrs are shown in Fig. 1C.

We used samples of bovine bone because of the similarities to human mandibular bone in both mechanical properties and the relation between cancellous and cortical bone.^{8,9} Bone samples were free from any musculoskeletal disorder or osteopenia. Samples were cleaned and all soft tissues removed, and then immersed in a solution of sterile saline and ethanol (1: 1), to minimise any thermophysical or mechanical changes to the proteins in the bones. The samples were sawn into blocks approximately 60 × 60 × 10 mm³, and then clamped in a Chiron Model FZ 12 MT CNC Vertical Machining Center with Fanuc 31i B5 5 Axes Continuous Path Control as a drilling robot. The tools were used according to the man-

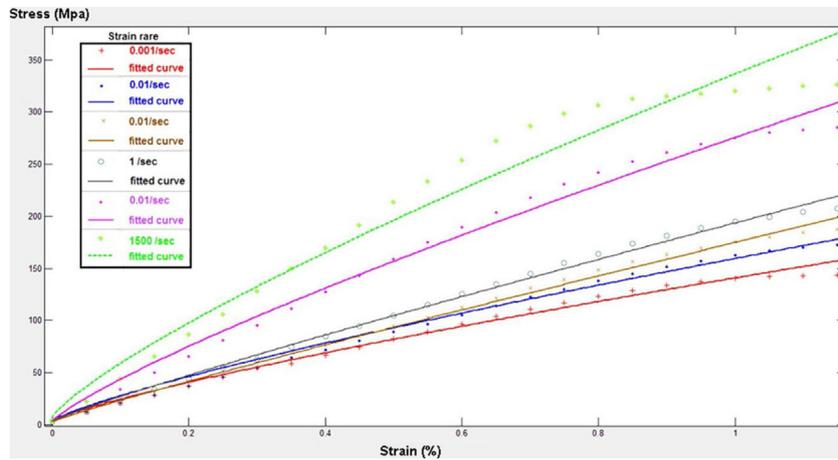


Fig. 2. Surface fitting of split Hopkinson pressure bar results (20 °C and different strain rate) on Johnson-Cook material using Matlab software for samples of bovine bone.

ufacturer's instructions (Wilson Precision Tool, Inc), and all tests done at 20 °C.

Instead of drilling in one step (associated with trauma because of intense force), the conical burr was used.¹⁰ To use this, we made a preliminary hole with a diameter of 2 mm under the same conditions with a conventional WC drill. Next, we made a bony osteotomy 5 mm deep. The Chiron Model FZ 12 MT CNC Vertical Machining Center with three degrees of freedom was used throughout to reduce inconvenient errors caused by surgeon's hands.

Saline solution was used to remove debris and for cooling. After drilling of each hole, the temperature of the burr was measured by an infrared thermometer (FLIR TG165, Wilsonville) placed at a standard distance of 12 cm from each sample. After drilling of 15 holes by each burr and before SEM analysis, burrs were disinfected using ultrasonic cleaning (water at 37 °C) for 10 minutes, then washed with water and dried with compressed air jets. After drilling 15 times with each instrument, the wear of the tool was evaluated using SEM (with EDAX attachment, Carl-Zeiss EVO MA15). EDAX spectra were collected on the Zeiss Ultra Plus equipped with an EDAX detector (Oxford, Aztec-X-80) using AZTEC software (Oxford Instruments). Tool wear was measured in relation to the edge of the new tool (in mm). Tool wear using SPIP software (version 6.4, Image Metrology A/S) was measured and reported.

This measurement was also repeated for both types of instrument after drilling 30 and 45 times. All the tests were repeated three times and the mean values of the burr temperature and tool wear have been reported. Based on the preliminary test and review of relevant publications, the rotating speed of the milling tool and feed-rate were chosen to be 800 rpm and 0.02 mm/m respectively.¹¹ The experiments were made at 20 °C room temperature and 20% humidity.

Finite Element Analysis (FEA)

FEA is a well-known computational approach to understanding the biomechanical conditions during osteotomy. With the prediction by FEA of mechanical and thermal stress during osteotomy, osteonecrosis could be avoided. Each simulation run lasted about 21 hours with an Intel Core i73.5-GHz CPU and 16 GB of RAM. To use FEA we chose a piece of mandible that had a hole in it. We constructed a finite element model based on the Johnson-Cook material model adapted for osteotomy.

Tool geometry and material specifications

Three-dimensional models of tool and bone are required for FEA, as more accurate and realistic models lead to more reliable results. The tool used in this study had complicated features from the perspective of modelling, so a high-resolution optical scanner (CometL3D; Carl Zeiss) was used for scanning the instruments. The camera's resolution was set to 8 megapixels using blue light-emitting diode (LED) scanning. Datasets were converted into STL files using software (Colin 3D; Carl Zeiss), and these files were imported to DEFORM-V11 (SFTC, Scientific Forming Technologies Corporation). For definition of material properties of the WC burr, we used the library of DEFORM-V11 and for the material properties of the ZrO₂ burr the data were imported to DEFORM-V11.¹² Solid mesh was generated with 23915 elements and 5930 nodes for burrs. For increasing accuracy of the simulation the mesh was refined at the drilling site. The environment temperature in the simulation was set to 20 °C. The friction coefficient between instrument and bone was considered 0.25 for the ZrO₂ tool and 0.4 for the WC tool.¹³

Definition of bone material model

During drilling and osteotomy, the bone withstands mechanical and thermal stresses, which leads to plastic deformation.

Table 1
Constants used for the finite element analysis.

Property	Value
Young's modulus ¹³	1.0e10 kg m ⁻¹ s ⁻²
Poisson's ratio ¹⁴	0.36
Thermal conductivity ¹⁵	0.64 W/mK
Specific heat ¹⁵	1216 J/kgK
Emissivity ¹⁶	0.96
Density ¹⁴	2.00e3 kg/m ³

We used the Johnson-Cook model for modelling of bone material properties during drilling (see Eq. (1) below). To find the measurements of the Johnson-Cook equation for bone, we used the split Hopkinson pressure bar test (SHPBT) on the samples and the results fitted the Johnson-Cook equation. A multilevel surface fitting technique in different temperature and strain rates was used in Matlab R2015a software (Mathworks Inc). A sample of surface fitting (20 °C and different strain rate) is shown in Fig. 2 (Confidence level 99.5%).

The constant variables were obtained: $A = 2.8$, $B = 139.5$, $n = 0.8$, $C = 0.027$, $\alpha = 0.025$ and used in the following relation that relates the stress, $\bar{\sigma}$ to the effective plastic strain, $\bar{\epsilon}$ as

$$\bar{\sigma} = (A + B\bar{\epsilon}^n) \left(1 + C \ln \left(\frac{\dot{\epsilon}}{\dot{\epsilon}_0} \right) \right) \left(\frac{\dot{\epsilon}}{\dot{\epsilon}_0} \right)^\alpha \quad (1)$$

Other variables used in the FEA are shown in Table 1.

The thermal conductivity coefficient of liquid coolant was 8000 W/m²K.¹⁷ Like the experimental test, the model in the FEA had an initial hole 2 mm in diameter. The hole was then extended using the burr.

Statistical analysis

The main outcome measurements (temperature and tool wear) are expressed as mean (SD), and the *t* test was used to compare temperature and tool wear between the two types of burr (ZrO₂ and WC). Additionally this method is useful for comparison of two variables that may be related in some features (in this study macro geometry). IBM SPSS Statistics for Windows, (version 22, IBM Corp.) was used for the analysis. We found significant differences in the temperature measurements in the cortical bone with the two types of tool ($p = 0.020$).

Results

Tool wear

The rate of tool wear increased with the increasing number of holes in both tools; however, this was less for the ZrO₂ than the WC tool (Figs. 3A and B). For this reason the overall wear of the ZrO₂ tool after the drilling of 45 holes was about half that of the WC tool (11 compared with 25 μm, Fig. 3C), and the *t* test indicated that the difference between the two types after the drilling of 45 holes was significant ($p = 0.044$).

Tool wear increased rapidly after 30 episodes of drilling in the WC burrs, while the ZrO₂ instrument was still sharp even after drilling 30 times.

The edges of both burrs are shown in Fig. 4. Column A shows the WC burr and column B the ZrO₂ burr.

Temperature

The mean (SD) temperature of the WC burr using the infrared thermometer was 38.3 (5.02) °C and for the ZrO₂ 36.4 (3.46) °C after drilling 45 holes. Generally, when the number of drilled holes increased the temperature increased in both burrs, that in the WC burr increased more than that in the ZrO₂ burr, and the difference after drilling 45 holes was significant ($p = 0.011$). As the number of holes increased, the difference between temperatures of the burrs also increased, possibly as a result of relatively more tool wear in the WC burr than the ZrO₂ burr.

FEA results

During the experiments and the osteotomy the diameter of the conical form of burr constantly changed, which led to an unsteady temperature. When cooling was not used, the temperature could rise up to 150 °C. Fig. 5A shows one of the middle steps of the FEA of the WC burr. The temperature analysis of the bone is shown in Fig. 5B. The points with the highest temperatures (about 60 °C) and more wear of the tool are shown in Fig. 5C. The tools became worn in the area of the highest temperatures. The FEA results confirm the data from the SEM.

The temperature profile from the drilled bone surface to a point under 2.2 mm of the surface for both burrs is shown in Fig. 5D. As shown in the diagram the temperature of the drilled bone surface of the ZrO₂ burr is less than that of the WC burr.

Discussion

Tool material

Zirconium dioxide or zirconia is useful for drilling bone because of its mechanical properties and biocompatibility, reliability, strength, and resistance to corrosion.¹⁸ Some studies have shown that the heat generated by a ceramic instrument in osteotomy is greater than that of the steel burr, but this increase in temperature does not have adverse effects on the bone.¹⁹ Harder et al reported no significant differences in this regard between ceramic and steel burrs.²⁰ There are reports on the effect of the instrument's material on the temperature and generation of heat,⁹ and some studies claimed that the tool material does not have a significant effect on the heat generation during the osteotomy.²⁰ However, despite growing advances in the manufacturing of ceramic burrs, only a limited number of studies have tried to address such an

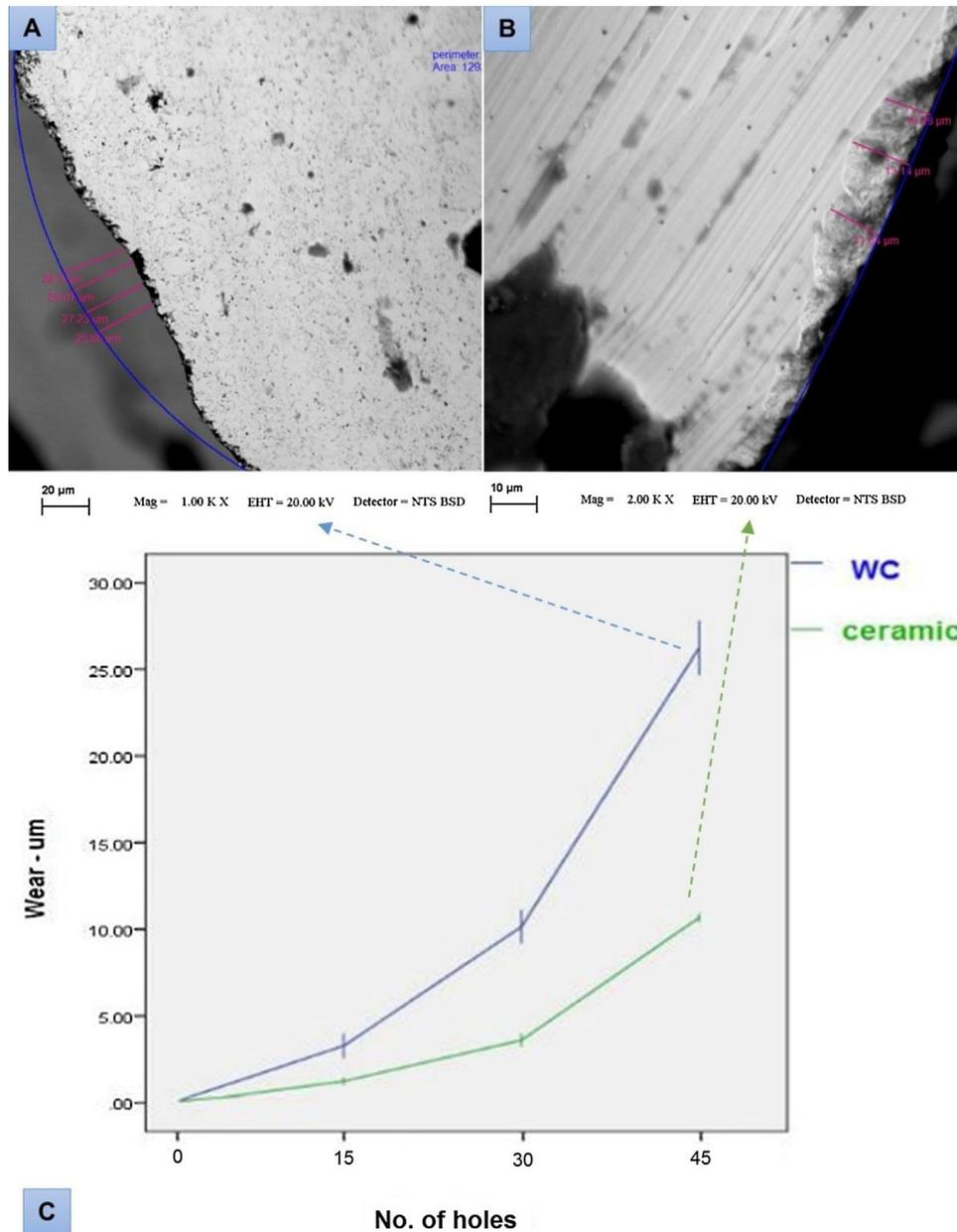


Fig. 3. (A) Wear of the tungsten carbide (WC) tool after drilling 45 holes in the same conditions. (B) Wear of the zirconium dioxide (ZrO₂) tool after drilling 45 holes in the same conditions. (C) Comparison of the wear of the ZrO₂ and WC tools.

important effect, and there is still a lack of consensus when it comes to its dental applications.²⁰ This motivated our choice of material for the present study.

For the assessment of the wear of the tool, we used optical microscopes and SEM.^{9,21,22} Some studies have reported changes in chemical properties of the surgical tool after drilling 50 times,²² and studies on osteoprotegerin suggest that after about 50 times, healing differs significantly and that could be a limiting factor in the use of the drill. This could be the effect of tool wear and surface integrity in the region of osseointegration. Although in some cases cooling is used to prevent an increase in the temperature, operation

with a worn tool can increase the temperature,²³ reduce the surface integrity of the bone, and also damage the bone.⁹ It has been reported that the rise in temperature that follows excessive use of the surgical tool will have an impact on bone remodelling because of the effect of the tool's wear on the quality of the surface of the hole.²¹

Koo et al¹⁹ examined surgical steel drills coated with titanium nitride, as well as those coated with WC, and zirconia. They investigated the tool wear using temperature measurement as a dependent factor.¹⁹ We measured tool wear directly by SEM and image processing software.

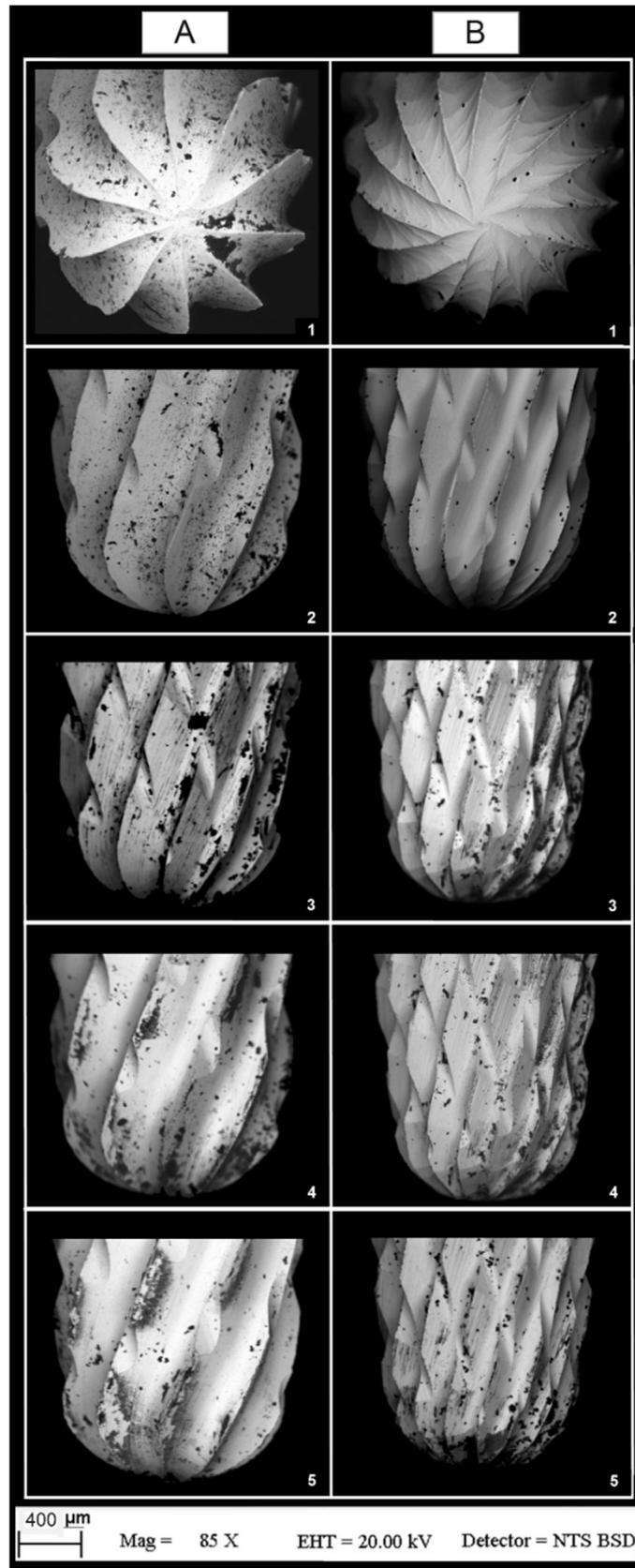


Fig. 4. Comparison of the wear between the zirconium oxide (column B) and the tungsten carbide (column A) tools: 1 and 2 = new burrs; 3 = after drilling 15 holes; 4 = after drilling 30 holes; and 5 = after drilling 45 holes.

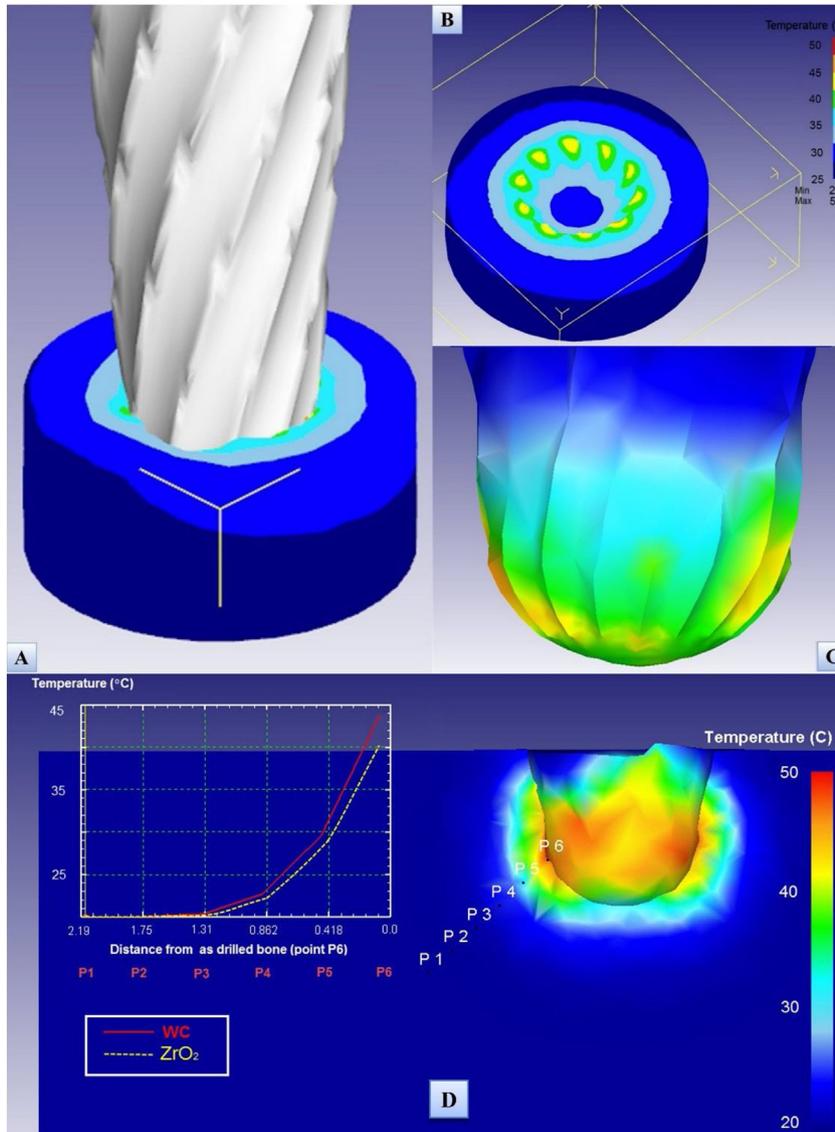


Fig. 5. (A–C) Temperature profiles of tool and bone samples. (D) Temperature of the two burrs at different depths of bone drilling.

Temperature

Infrared thermography during osteotomy with cylindrical and conical burrs has been investigated, and drill geometry has an important role in the temperature of the osteotomy.¹⁰ The comparison of temperature and tool wear has been studied between stainless steel and ceramic tool in osteotomy of the implant bed.⁹ These results are consistent those of the present study with regard to comparison of temperature between ceramic and metal burrs. The temperature in the standard method compared with the single-drill technique has been investigated by Lucchiari et al¹ and the results indicated that there was no significant difference in outcome when a liquid coolant was used compared with when it was not used.¹ Any change in the geometry of the instrument will affect the amount of heat generated.²⁴ It seems that one of the reasons for increasing the temperature of the tool is erosion at the

edge that necessitates more force being necessary for its use and finally results in more mechanical and thermal stresses.

Change in chemical properties

Fig. 6 shows the edge of the instrument that has been eroded. To investigate this edge better by SEM and analysis of images with AZTEC software, we looked at a line scan of different elements on the edge. As shown in Fig. 6, two separate parts in 25 μm of cutting edge of burr were considered. In the first part (approximately 10 μm long) the chemical composition was changed, and in the second part phosphorus and calcium (base elements of bone) were found. In the first part tool wear was seen on sharp edges, and in the second part debris had adhered to the lateral surface of the burr. Staroveski et al reported similar tool wear at the cutting edge of bone-drilling instruments.²⁵

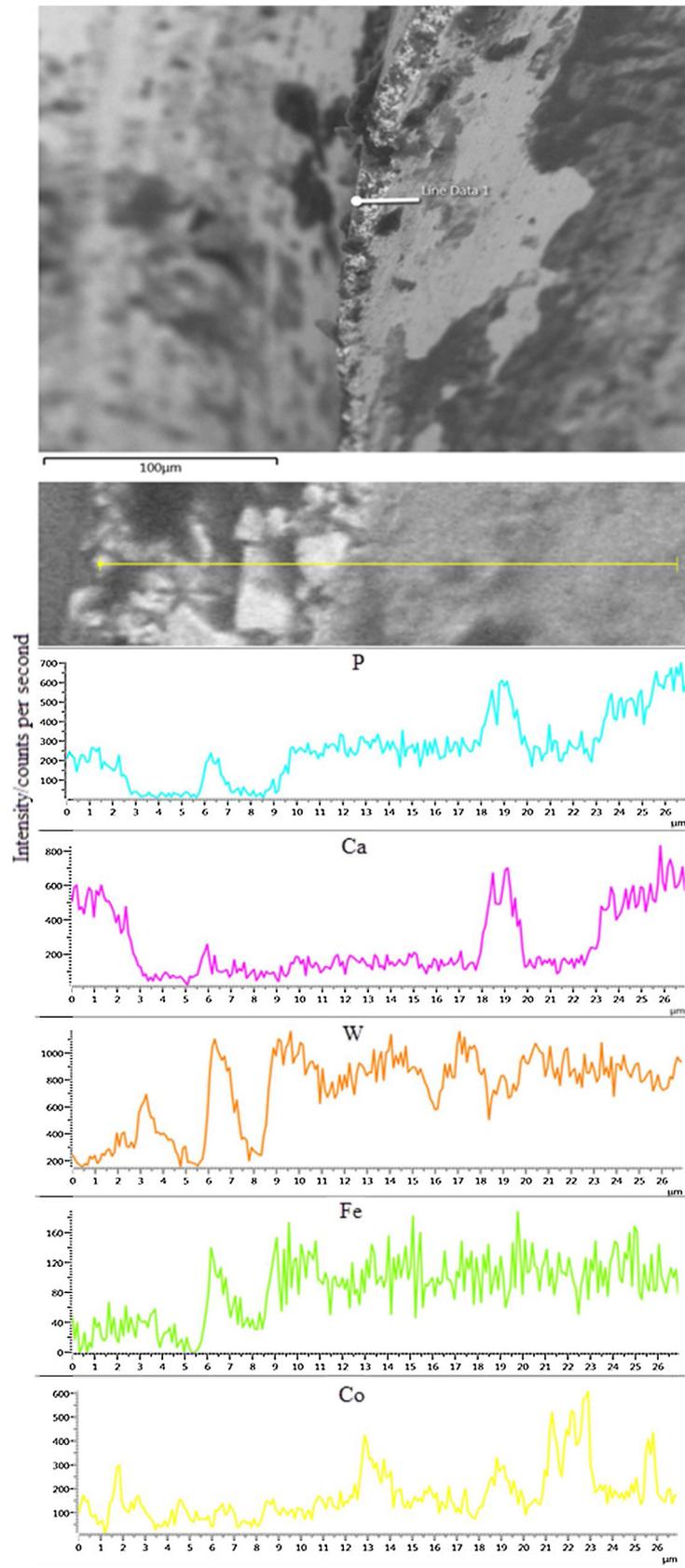


Fig. 6. Chemical composition of tip of the tungsten carbide drill.

Ceramics have major advantages such as resistance to wear and corrosion, and biocompatibility, but their application as surgical instruments has been restricted because of low thermal conductivity, cost, and brittleness. In this study the cost of the burrs was the same, and the ZrO₂ tool was made up of two sections to increase the flexibility. To compensate for the low heat transfer coefficient of the ZrO₂, a jet of mixed air and saline with a flow rate of 200 ml/minute was used externally. While the heat generated during osteotomy by the ceramic burr was being controlled, there was less tool wear than with the WC burr. When we used ceramic burrs the need for replacement because the tool was worn was reduced, and the geometry of the hole was more accurate.⁹

Conclusion

A rise in temperature during the drilling of bone may lead to osteonecrosis. The conflicting results of temperature during drilling by WC and ZrO₂ burrs indicated that it was a complex phenomenon. Our results show that more frequent use of the ZrO₂ burr necessitates cooling it to avoid necrosis. However, the ZrO₂ burr is recommended for superficial rather than deep holes in bone. If the affordable cooling system is used for the ZrO₂ tool, the tool wears less in comparison with the WC burr, and if it is used continuously, a lower temperature is achieved than with the WC burr.

Conflict of interest

We have no conflicts of interest.

Ethics statement/confirmation of patients' permission

Neither is required.

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