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Bone Cell Protection

Temperature Elevation During Implant Osteotomy

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I. Introduction

Dental implantology has revolutionized modern dentistry, offering a reliable solution for edentulism and tooth loss. Successful osseointegration—the direct structural and functional connection between living bone and the implant surface—is crucial for long-term implant stability[1]. However, numerous factors influence the outcome of dental implants, including but not limited to patient-related factors both local and systemic, occlusion, implant design, and surgical considerations--such as heat generation during osteotomy site preparation. Thermal damage can be attributed to a number of factors, resulting in difficulty in control, which is of concern as it may account for bone necrosis, delayed healing, bony remodeling, or a failure in osseointegration in the form of immediate implant failure.

During site preparation, an osteotomy is gradually widened with incremental increases in drill bit diameters. Friction between the drill and bone results in an exothermic reaction, in which the heat is distributed in the surrounding bone. Research provides a critical safety threshold of 50°C, with a maximum duration of 30 seconds, otherwise, risk increases for irreversible bone damage with aberrations in osteocyte and osteoclast activity. Thus, the most important variable to consider in regards to heat generation, when assessing a drilling system is optimization in time, for the sake of efficiency and minimization of heat generation for improved bone remodeling.

1.1 Biological Response of Bone to Heat

Bone is a highly dynamic and vascularized tissue that is more sensitive in regenerative capacity to thermal response compared to its soft tissue counterpart. Thermal injury in bone primarily affects:

- Cellular constituents of the bone (e.g. osteocytes, osteoblasts, osteoclasts) through impaired osteogenesis, cellular apoptosis, and necrosis[2].
- Extracellular matrix, such as collagen, alkaline phophatase, which denature at 60°C and 56°C with >10 second exposures, respectively. Irreversible changes to dog femoral bone tissue in vivo were seen at 50°C, in rabbit tissue at 47°C for one minute, and in Lundskog's study, 50°C for 30 seconds[3]
- Key enzymes such as diaphorase, responsible for cellular aerobic and anaerobic function, begins to deactivate at 50°C[3]. Vascular structures in the form of delicate capillary systems that may result in ischemia and resorption over time[1]

Therefore, controlling heat generation during the procedure is critical[4].

Heat shock is a cellular, cytoprotective response to elevated temperatures, which triggers a cascade of specific proteins, genes, and transcription factors to minimize effects of stress-induced damage[5]. Effects of heat shock proteins are assessed through measures of cell vitality and function with cell viability and response.

As mentioned, both the temperature and duration of exposure dictate the amount and type of damage bone tissue incurs.

In an experiment by Dolan et. al, bone cells were heat shocked[6] (Table 1.2) and evaluated for viability, necrosis and apoptosis immediately after 1, 12, 24 and 96 hours using murine osteoblasts-like and osteocyte-like cells. Regeneration capacity was also evaluated by quantifying proliferation, differentiation and mineralization at 7- and 14-days recovery using murine osteoblasts-like and mesenchymal stem cells. Cells exposed to temperatures of 45°C (any duration) showed complete recovery by 4 days as indicated by percent necrosis, viability and proliferation. After 14 days recovery, cells showed increased alkaline phosphatase and calcium secretion compared to the control, indicating a possible therapeutic capability of mild heat treatment. Cells heated to higher temperatures did not show this recovery or a regeneration capacity compared to control. In addition, calcium deposition is significantly decreased at 47°C for one minute as well as 60°C for 30 seconds or one minute. As the temperature and duration of heat exposure increases, the amount of damage noticed increases, the worst results being for 60°C for one minute. The findings of their study suggest minimizing temperature elevation to less than 47°C for one minute in order to reduce the number of necrotic and apoptotic cells but also induce mineralized matrix production.

Similarly, a study from Lundskog et. al noted similar results from heat shock, reporting immediate cell death at 70°C and a correlating increase in extent of cell death by radius with lengthened exposure to heat [5,7-12].

1.2 Factors Influencing Heat Generation During Drilling

Heat generation during osteotomy site preparation is influenced by multiple factors, including drill design, drilling technique, cooling methods, and bone density. Each of these factors has a role in determining the extent of temperature rising, as well as how the bone fast the bone can return to its starting temperature.

1.2.1 Drill Design and Geometry

The physical characteristics of drill bits (including the diameter, shape, flute design, and coating) can determine the cutting efficiency, but also influence frictional heat generation. Studies have shown that multi-fluted drills generate more heat than two-fluted drills due to their increased contact with bone[13]. Additionally, dull or worn burs require greater force to cut through bone, which increases the friction and, in turn, temperature[14]. Newer implant drill systems such as Loocid Bone Cell Protection (BCP) incorporate geometric designs to reduce friction and improve heat dissipation. In this study, we aimed to evaluate if these design modifications can effectively minimize temperature elevation compared to conventional drills and similar osseodensification burs.

1.2.2 Drilling Speed and Pressure

Drilling speed is a major determinant of heat generation. Higher speeds (>2000 RPM) can reduce heat generation by shortening the duration of drill-to-bone contact, while slower speeds (<500 RPM) can result in prolonged friction and excessive heat production[10]. However, optimal speeds for osteotomy site preparation vary between manufacturers and drilling protocols, and typically range from 800-1500 RPM. This range aims to balance efficiency and heat control.

In addition, the operator pressure used while drilling directly affects heat accumulation as well. Excessive force results in increased friction, while insufficient pressure can lead to inefficient cutting and in turn require longer drilling time. Maintaining a controlled and consistent pressure is key to preventing unnecessary thermal damage.

1.2.3 Sequential vs. Single Drilling Protocols

Traditional implant site preparation involves a sequential drilling protocol, where multiple drill sizes are used in a step-wise fashion to progressively widen the osteotomy site. This method is believed to reduce the temperature spiking, by distributing heat production across different steps[15].

In contrast, single drilling protocols (where one final drill is used directly) may lead to higher temperature increases due to the greater amounts of bone removal in a single step. Recent innovations such as the Nobel N1 drills claim to optimize single drilling efficiency while limiting heat generation.

In this study, we will evaluate both drilling protocols to determine which method better preserves bone cell viability while maintaining clinical efficiency.

1.2.4 Irrigation and Cooling Systems

One of the most effective ways to control/reduce temperature elevation during osteotomy site preparation is external and internal irrigation. Saline and sterile water irrigation cools both the drill bit and the surrounding bone, preventing excessive heat buildup. Studies suggest that continuous irrigation reduces temperature as much as 40% compared to drilling without irrigation[16].

However, irrigation may not be sufficient alone, if the drill design generates excessive heat. Therefore, a combination of an efficient drill system and adequate cooling measures is critical in limiting thermal damage.

1.3 Clinical Consequences of Thermal Damage

The exact temperature at which bone necrosis begins is directly related to two factors: time and temperature. While studies have shown beneficial effects in mild and shortened heat shocking for enzymatic and cellular composition around 45°C, an exact time and temperature is too difficult to pinpoint at which irreversible bony necrosis is noted. Most literature conservatively cite 50°C for 30 seconds as the lower threshold[10]. As the duration of heat exposure lengthens, the radius of damaged tissue also increases with an initial disruption of vascular structures. Large vessels experience hyperemia while capillary beds experience ischemia. Over the course of 14 days, capillaries reorganize and elongate, adjacent adipocytes resorb and are replaced with decreased morphology, leading to bone resorption[1,6].

Delayed symptoms of thermal osteonecrosis can clinically manifest as poor primary stability, marginal bone loss, or early implant failure within the first few months following post-implant placement[17].

Patients with delayed healing require even greater attention to thermal protection. Risk factors include:

- Smoking- nicotine reduces blood flow and impairs bone repair
- Osteoporosis- compromised bone density increases susceptibility to thermal damage
- Diabetes- poor metabolic control slows down bone healing and osseointegration
- Age- bone turnover occurs at a reduced rate with old age, and can affect implant stability

In these populations, implant systems that minimize heat may be beneficial in enhancing implant outcomes.

1.4 **Heat Generation from Implant Drills[18]**

Heat generation during implant osteotomy is primarily attributed to mechanical interactions that occur at the drill-bone interface. As illustrated in Figure 1, the cutting process involves three key shear zones:

1. The primary shear zone- Where the bone undergoes plastic deformation
2. The secondary shear zone- Where friction occurs between the flowing bone chips and the rake face of the drill

3. The tertiary shear zone- Where the clearance face of the drill rubs against the freshly cut bone surface

Each of these zones contributes to thermal buildup, with friction and plastic deformation being the dominant sources. Drill geometry further influences thermal generation, as parameters such as rake angle (γ), clearance angle (α), and shear angle (ϕ) modulate chip flow and frictional contact. An increase in rake angle can facilitate smoother chip removal (which can reduce heat), whereas insufficient clearance may lead to excessive friction, elevating surface temperature. Understanding these mechanisms is essential, as excessive thermal elevation above 47 °C for prolonged periods can lead to osteonecrosis and compromised osseointegration.

II. Research Aims/Hypothesis

Implant osteotomies can cause thermal osteonecrosis with increased osteoclastic resorption, delayed bone healing and potential complications. The primary aim of this study was to compare BCP, standard tapered, multi-fluted, and single protocol drill bits in terms of temperature generated during implant bed preparation.

Our Primary hypotheses:

- Null hypothesis: There will be no difference in the temperatures generated among the variation of drill bits. Temperatures generated by drill bits will stay below critical bone cell temperatures

- Alternative hypothesis: The mean temperature generated will be significantly lower for BCP drill bits in comparison to other drill bits

Our secondary aim was to study if reusing the same drill will cause an increase in thermal generation.

- Null hypothesis: There will be no difference in thermal generation between the first, second, and third use of each drill.
- Alternative hypothesis: There is an increase in thermal generation between the first, second, and third use of each drill.

III. Significance

Despite extensive research on thermal damage during osteotomy site preparation, there remains a lack of consensus on the most effective drill system for reducing heat generation. Temperatures created during osteotomy preparation with standard implant drill bits can be high enough to cause osteocyte damage and death. This can compromise implant stability in the weeks after placement, delay the healing process and create complications like e.g., bone loss. Protection of osteocytes, by minimizing or eliminating thermal damage during osteotomy preparation, leaves a maximum of healthy bone cells behind, which can promote osseointegration and bone healing. This is particularly important when considering advanced treatment protocols including early or immediate loading or treating patients with delayed bone healing (e.g. smoking, advanced age, medical comorbidities or medications). The BCP drills claim to keep temperatures below 50°C, preventing cellular damage and enhancing osseointegration potential. However, independent studies validating these claims are limited. Additionally, a more efficient workflow, with fewer drills, can significantly shorten overall procedures benefiting patients and clinicians. By addressing these questions, this research will aid in providing insight into heat generation of industry standard burs in implant osteotomy techniques, helping clinicians assess potential for bone necroses for enhanced patient outcomes through implant survival.

IV. Materials and Methods

Bone Specimens

The artificial bone similes (BS180035-120035-180035, BoneSim, USA) are engineered matrices of reconstituted viable bone with a 3mm cortical layer (simulating type 1 bone)[19], 12mm cancellous layer (simulating type 2 bone)[19], and diameter of 58mm and are used as the medium in which the implant beds are prepared. The organic bone samples have similar properties to human cortical bone, shown in Table 1.3 (Bonesim, USA).[20, 21] Most importantly for this study the Specific heat capacity, or simply specific heat is identical with human bone. Specific heat refers to the heat capacity per unit mass of a pure substance. In other words, it is defined as the amount of heat needed to increase the temperature of 1kg of a material by 1K and is expressed in terms of J/kg·K or equivalently J/kg·°C.

Standardized bone analogs will act as a controlled variable between different drill designs and drilling protocols with uniform ratios of cortical to cancellous bone maintained throughout the testing. Artificially generated bone provide a homologous testing site as compared to harvested block xenografts that have varying densities and characteristics (i.e. femur of a rabbit, jaw of a dog), depicted in Figure 2.1.

Using high precision Computer Numeric Control (CNC) machines, the bonesims are cut into strips specifically made for each drill bit tested. The exact location of each implant bed preparation was marked. Each implant bed preparation was placed so that its periphery, post preparation, maintained a 3mm safety margin from neighboring samples and 0.5mm away from the lateral bone wall. An infrared camera was trained directly on the lateral bone wall, yielding a 0.5mm distance of bone between the implant bed preparation and the thermal measuring device. While 0.35mm of remaining bone wall would be the preferred distance from the thermal measuring devices, it is not viable to serve as structural support without risk of fracture[22].

The bonesim strips were soaked in room temperature saline for at least 20 minutes prior to drilling to simulate a more fluid environment.

Drills & Drilling Groups

The different surgical drills bits used for implant bed preparation are shown below:

- Standard tapered drill bits : ø 2.0, ø 3.5, ø 4.3mm
- BCP drill bits: ø 2.0, ø 3.7, ø 4.2mm
- Multi-fluted drill bits: ø 1.6, ø 3.5
- Single Protocol drill bits: ø 1.8

Surgical drill bits were used to prepare an implant bed with irrigation using a custom-built drill press with a load of 2.3kg (mimicking an average clinician pressure/weight) in combination with a W&H implant motor (W&H Group, Austria) set to a spindle speed of 1000 rpm. Each new surgical drill bit was used 3 times under these testing conditions.

Drilling Protocols:

Single Drilling Protocol (Standard, BCP, and Single-Drill):

Each individual-sized drill was used to perform the final osteotomy to full depth (10mm). The osteotomy was performed in one continuous motion to full depth without any intermittent drilling technique. The rounds per minute (rpm) used for every drill bit followed the manufacturer's instruction for use (IFU). All drilling was executed with continuous irrigation.

Sequential Drilling Protocol (VERSAH):

Drill bits were used in sequence to incrementally widen the osteotomy. The osteotomy was performed in one continuous motion to full depth without any intermittent drilling technique. The sequential drilling protocol followed the manufacturer's instruction for use (IFU). All drilling was executed with continuous irrigation. The sequential drilling protocol was performed in the VERSAH multi-fluted group, as described, imitating clinical use.

All drill bits will be set at a speed of 1000 rpm and depth of 10mm.

Temperature Measurement[22]

The thermal data acquisition was executed by the infrared thermal camera. A FLIR T865 infrared camera (FLIR Systems Inc., Oregon, USA) with a special macro feature was positioned on a tripod 80mm from the edge of the bonesim, separated from the implant bed preparation by 0.5mm of bone wall. The thermal camera has a standard temperature range of -50-152.1°C and accuracy as good as 1°C/1%, 1-Touch Level/Span contrast enhancement, and laser–assisted autofocus[22]. A wax barrier at least 5 mm high on the outer top edge of the bonesim prevents any irrigation water from seeping onto the outer lateral surface of the bonesim, obstructing the view of the thermal camera. Videos of the implant bed preparation were recorded on the lateral surface of the bonesim in a rainbow palette (20 colors) using FLIR ResearchIR. Temperature readings were recorded before, during and after the implant bed preparation to determine the bone base and maximum temperature, as well as the time required for temperatures to be within 18°C of the base temperature, if such high heat readings were recorded. Maxillary temperatures listed in literature range from 25-32°C (average 29.22°C)[23]. With 50°C as the threshold for damage, a worst-case scenario is a base temperature of 32°C, producing a maximum temperature increase of 18°C for 30 seconds. Base temperatures do not need to be kept consistent since the first law of thermodynamics concludes that the amount of heat absorbed by the bonesim and its subsequent temperature rise are independent of the base temperature of the sample[24]. Since the standard camera was used multiple examiners were not needed for this study.

Figure 2.2 demonstrates the way in which temperature readings during implant bed preparation are collected using the infrared camera. Infrared videos acquired using the infrared camera were analyzed in the range of the 10mm implant osteotomy. Average temperatures were recorded 0.5mm away from the periphery of the implant bed during the complete duration of the preparation starting from the top of the preparation continuously to a depth of 10mm.

V. Data Analysis

A sample size of n=3 specimens per group for a total of 27 specimens were used in this study.

Statistical Analysis – Descriptive statistics (i.e. means, standard deviations, medians, and interquartile ranges) will be calculated for continuous variables; frequencies and percentages for categorical variables were calculated. The assumption of normality was assessed graphically as well as using the Shapiro-Wilk test. The Analysis of Covariance (ANCOVA) test was used to assess the association between predictor variables and highest temperature generated adjusting for baseline temperature. The Analysis of Variance (ANOVA) test was used to assess the association between type of drill bit and difference in temperature from baseline to highest temperature generated. The ANOVA was also used to explore associations of predictors with the outcome “time for temperature to return to baseline”. P-values lower than 0.05 were considered statistically significant. SAS Version 9.4 (SAS Institute Inc, Cary, NC) was used for analysis.

VI. Results

6.1 Highest Temperature (Table 6.1, Graph 6.1)

One of the outcomes measured was the highest temperature reached when preparing the osteotomy site. On average, the highest temperature reached in all groups was 69.44 °C ±40.19 °C. When comparing drill groups, the highest mean temperature was found in the multi-fluted drill group, with the mean temperature recorded at 131.33°C ± 33.42 °C. Standard tapered drill bits exhibited an average temperature of 61.67 °C ±23.20 °C. Single protocol drills maintained a lower average temperature of 55.33 °C ± 10.69 °C. The lowest peak temperature was noted in the BCP drills, with mean temperatures of 40.67 °C ± 6.08 °C. When looking at the ANCOVA analysis to look at highest temperatures (adjusting for the difference in start temperatures of ~2-3 °C), there was a statistically significant lower average highest temperature when comparing the BCP group to multi-fluted ($p<0.0001$) as well as the standard tapered group to the multi-fluted group ($p<0.0001$). While the single protocol group had a lower average highest temperature compared to multi-fluted, the difference between the 2 groups was not statistically significant ($p= 0.0795$). This indicates that a single drill protocol compared to the multi-fluted drills do produce higher temperatures in general, and while the differences in mean temperatures are different, they can vary while drilling (standard deviation), making both drills prone to higher temperatures above 50 °C. *(See appendix, table 6.1 for details)*

6.2 Change in Temperature (Table 6.1, Graph 6.2)

Further analysis assessed differences in temperature increase among the groups. The mean change in temperature for all groups was 45.81 °C ±40.45 °C, satisfying the safety threshold with a 45 °C change in temperature within the site. When comparing the temperature changes between individual groups, the highest mean difference was noted in the multi-fluted group, with a mean of 109.00 °C ±32.75 °C. Standard tapered drill groups yielded a mean change of 36.89 °C± 22.90 °C. Single protocol drill group had a mean change of 30.00 °C±10.44 °C. The lowest mean change was noted in the BCP drills, with a mean of 17.89 °C± 6.35 °C.

When using an ANOVA test to compare the results between groups, we noted that all groups were statistically significant when compared against the multi-fluted group. BCP and standard tapered drill bits had statistically significant lowered changes in temperature compared to multi-fluted groups (p-value of <0.0001), while the single protocol group had a p-value= 0.0001 compared to the multi-fluted group. In short, comparisons of eachgroup to multi-fluted groups held a significantly lower change in temperature while drilling. With exclusion of multi-fluted group, there was no statistical significance in difference in temperature. *(See appendix, table 6.1 for details)*

6.3 Time for Temperature to Return to Baseline (Table 6.1, Graph 6.3)

Temperature regression was also measured in osteotomy sites. On average, it took the bonesim models about 108.44 ±36.06 seconds to return to the baseline temperature, after drilling. Multi-fluted groups had the longest mean time to return to initial temperature measurements, with a time of 129.50 ±16.45 seconds. The second highest group was noted in the BCP group, with a time of 111.67 ±40.23 seconds. This was followed by standard tapered drill group, with a time of 101.11 ±40.48 seconds, and lastly the single protocol group, with a time of 78.67± 15.95 seconds. Minor variations existed among groups but were likely controlled for due to the uniformity of drilling surface for each drill, which resulted in similar heat propagation through the model. The external testing environment (i.e. temperature, humidity, PSI, etc) of the room was standardized for all trials as all testing was completed in one session. *(Please refer to appendix, table 6.1 for details)*

6.4 Time Above 50 °C (Table 6.1, Graph 6.4)

On average, the time that the bonesims were above 50 °C was 5.74 ±7.62 seconds. The maximum time that the bonesim was above 50 °C was 28 seconds, as reported in the standard tapered drill group ø4.3mm diameter, drill bit, which was the largest in the study. Of note, the largest BCP drill bit diameter size of 4.2mm, which is comparable, did not pass the 50 °C, as claimed by their manufacturer. The highest average time above 50 °C was noted in the multi-fluted group, with an average of12.17 ±4.62 seconds. The next group was the standard tapered drill group, with a mean of 7.67 ±

9.91 seconds above 50 °C. This was followed by the single protocol group, with an average time of 4.33 ±4.04 seconds above 50 °C. *(Please refer to appendix, table 6.1 for details)*

6.5 The Influence of Number of Times a Drill was Used (Table 6.2, Graph 6.5-6.8)

In this study, we used each bur 3 times. This is to simulate clinical scenarios, as clinicians have a tendency to reuse implant drills for multiple patients. Industry standard sets a maximum limit of 20 times of use per drill but advise a safety range of 1-5 times per use. When comparing subsequent drill use, a marked rise in temperature is noted. The greatest temperature variation is observed between the first and the third group, with the average temperatures going from 67.00 °C ±29.90 °C, to 67.56 °C ± 44.94 °C, to 73.78 °C ±47.99 °C respectively. The difference in temperature (from start to highest temperature) is 43.44 °C ±29.68 °C, 43.44 °C ± 46.11 °C, and 50.56 °C ± 47.67 °C from the first to third use, respectively. The time for the temperature to return to baseline from first to third use is as follows: 104.56 ± 32.75 seconds, 106.44 ±43.16 seconds, and 114.33 ± 35.09 seconds.

Overall, when looking at these data points, this means that as you continually use the same drill bit repeatedly, this causes the bone to reach higher temperatures and takes the bone longer to cool down and return to baseline. However, this change is not statistically significant. *(Please refer to appendix, table 6.2 for details)*

VII. Discussion

7.1 Overview of Study Findings

The results of this study demonstrate significant differences in temperature generation among different implant systems, confirming that drill design plays a role in thermal control during the osteotomy site preparation. The BCP burs consistently maintained temperatures below the critical 50°C threshold, whereas the multi-fluted and standard tapered drills and single protocol drills produced higher temperatures, increasing the risk of thermal damage to the bone. Multi-fluted drills were statistically significantly higher in temperature changes compared to all drilling systems studied.

The significant temperature variations between drill systems suggest that heat production is influenced by multiple factors, including drill geometry, drilling protocol, and irrigation efficiency. A study by Aquilanti in 2023 examined the effect of irrigation efficiency, and noted that lower saline temperatures are effective in reducing the thermal generation during implant site preparation, but volume of saline used is not statistically significant in heat reduction. However, they saw that saline irrigation is critical, as lack of irrigation causes heat to increase to levels that can cause osteonecrosis[25].

These findings are clinically relevant as thermal osteonecrosis can impair osseointegration and implant stability, especially in high-risk patients. Our study further provides insights on how repeated drill usage affects temperature elevation, which raises concerns about the longevity and reusability of implant drills in our clinical practice.

7.2 Influence of Drill Design on Heat Generation

The BCP drills demonstrated the lowest peak temperatures amongst all tested groups, with the average temperatures staying below the 50°C threshold. This supports claims that the BCP drills' unique cutting geometry effectively reduces heat generation. In contrast, the multi-fluted drills produced the highest peak temperatures, which is anticipated, given the multi-fluted design of the drill, used in more dense Type-2 bone in a wide jump incrementally from one osteotomy size to the next. In having to increase nearly 2.0mm between drilling sequence, the small flutes will overcompensate in drilling duration, resulting in elongated drill to bone contact and heat generation.

7.2.1 Cutting Geometry and Flute Design

The differences in temperature can be attributed to the drill bit geometry. Literature has demonstrated that multi-fluted drills generally produce more friction and heat generation than those with fewer flutes[8]. The BCP drills' cutting-edge design most likely optimizes bone removal while minimizing friction, resulting in lower temperatures. The design of the BCP drills includes a larger helical angle, which can allow for the bone chips to be more easily removed from the osteotomy site, and reduce the time bone spends in secondary shear zone, which could in turn reduce the heat generation[18].

Conversely, multi-fluted drills are designed to condense bone rather than remove bone in sites with less dense bone. The choice to use a multi-fluted bur for the study was to confirm the nature of higher heat production from the anatomy of this implant design. Subjecting a multi-fluted bur to a single protocol drill sequence would inherently generate more heat due to increased resistance and frictional forces during osteotomy preparation [22]. For these situations, a smaller stepwise increment is needed to enlarge the osteotomy site in a controlled manner. In the VERSAH group, these flutes are not intended for cutting, therefore using these drills in a cutting manner can cause an increase in the primary and secondary shear stress, which can increase the heat generation significantly, as the flutes are not designed to effective cut or remove bone from the osteotomy site[18].

A study by Soldatos in 2022 examined the difference between straight and tapered implant drills and the thermal heat generation. In this study, they were able to determine that a tapered drill design caused significantly greater heat production when compared to straight drills[26]. This finding is supported by our study, which shows that a difference in the drill geometry influences the amount of heat generated during osteotomy preparation.

7.2.2 Impact of Drill Wear/ Reuse on Thermal Generation

Our study showed that there was a slight increase in temperature when reusing the drills, but this was only noted when observing the groups as averages. When looking at individual data points, we can appreciate that there is no clear trend in temperature increase when reusing the drills. This is also supported by multiple studies in literature, that have also not been able to clinically examine a difference in temperature use when reusing the same bur multiple times[11, 27-29]. A study by Möhlhenric[11] examined reusing the same drill 50 times, and noted that while there is deformation of the plastic and the drill[18], there is no statistically significant increase in temperature generation between the first use and the 50th use. Anecdotally, while we always state that reuse can cause an increase in heat generation, there is currently not any literature to support this claim. In our study, we also did not note a correlation between drill reuse and increase in thermal generation.

7.3 Comparison of Drilling Protocols: Single vs Sequential Drilling

One of the key findings in this study was the variation in thermal effects between single and sequential drilling protocols.

- Sequential Drilling: This method involves gradually increasing drill diameters. In studies, it has shown lower temperature spikes, as heat was distributed across multiple stages. Some studies have proven that sequential drilling results in less thermal damage as compared to single drilling, because less bone is removed with each drill, allowing the bone to cool to starting temperatures between each drill used[21].

- Single drilling: This method is faster, but also produced higher peak temperatures in our study, which is consistent with findings that removing a large amount of bone at once generates excessive frictional heat[24].

Interestingly, the single drill protocol group used in the study showed lower temperatures than standard single-drilling approaches but higher temperatures than sequential drilling methods. This suggests that changes to the drill design can reduce some of the risks associated with traditional single drilling protocols.

These findings also reinforce the importance of protocol selection based on patient-specific factors. Sequential drilling may be preferred for thermally sensitive cases, whereas single drilling may be acceptable with heat-optimized BCP drills.

7.4 Clinical Implications of Thermal Damage on Osseointegration

The biologic impact of heat on bone cells is well documented in literature. When exposed to elevated temperatures for prolonged time, bone cells undergo necrosis, apoptosis, and loss of regenerative capacity[6].

7.4.1 Vascular Changes and Bone Resorption

High temperatures primarily affect bone vasculature, leading to capillary occlusion and reduced blood supply to the implant site[1]. Over time, this can contribute to:

- Bone resorption, due to increased osteoclastic activity

- Delayed healing, caused by reduced angiogenesis and diminished osteoblastic function
- Marginal bone loss, particularly in patients with systemic conditions (e.g. diabetes, osteoporosis)[23].

7.4.2 Influence on Implant Stability

Heat-induced osteocyte damage can compromise early implant stability, increasing the risk of implant micromovement and failure. Studies have found that higher osteotomy temperatures correlate with poorer secondary stability and reduced bone-to-implant contact[20].

Therefore, selecting drill systems that prevent excessive heat buildup (such as the BCP drills) may play a significant role in enhancing long-term implant success.

7.5 Strategies for Minimizing Thermal Osteonecrosis

The results of this study support several key recommendations for reducing heat generation during implant osteotomy site preparation:

1. Optimized drill selection- Selecting drills with heat-minimizing design (such as BCP) can reduce temperature elevation and prevent excessive thermal damage.
2. Adequate irrigation- Ensuring continuous cooling with sterile saline can dissipate heat more effectively, especially in dense cortical bone[25, 30].

3. Drill replacement after a few uses- Reused drills could increase thermal risks, therefore clinicians should follow manufacturer recommendations regarding the number of times each bur can be used before replacement.
4. Customized drilling protocols- Sequential drilling should be considered for patients with compromised bone healing, whereas single drill protocols can be considered when using heat-efficient drills.

These strategies highlight the importance of evidence-based surgical planning for implants and each patient.

7.6 Limitations of the Study

A bench study holds many limitations, such as:

1. Single drilling protocol: The Nobel standard drills and Loocid BCP drills were all used as a single drilling protocol, which is not as clinically intended. This can therefore cause higher temperature readings in our study. Proper sequential use of these drills could result in lower temperatures in research and clinical scenarios. Another follow-up study would involve more analysis in the differences of single drilling versus sequential drilling.
2. Multi-fluted drilling protocol: Traditionally, multi-fluted burs are ideally used for osseodensification in type 3 or 4 bone. OD mode also requires drilling in a counterclockwise direction, which condenses bone and generates minimal heat. However, in our study, to maintain consistency of using all burs in a clockwise direction at the same RPM, the multi-fluted burs were used in a

setting apart from its intended design. This, combined with a large incremental stepwise protocol (increase in diameter of ~2mm between each drill) could be the reason behind such a statistically significantly higher temperatures. Due to the harder type 2 bone quality, we should have also ideally incorporated a smaller-increment stepwise protocol in order to allow for gradual increase in osteotomy size, and to prevent overheating and overcutting of the bone in this manner.

3. Bonesim quality- All the bonesims are standardized and are created to simulate a harder type 2 bone. While it is recommended that type 2 or 3 bone is the best for implant placement, a harder bone quality can promote higher temperatures due to the increased force required for bone cutting and osteotomy site preparation. In patients with softer bone, less cutting is required, which can reduce peak temperatures reached.
4. Temperature of the bone- Our thermal camera was used to measure the hottest area of bone during drilling and cooling. This means that we could only measure a single point on the bone. The clinical significance is that the heat dissipates throughout the entire bonesim. According to the Lundskog study, cells die immediately once they reach 70°C. Since we only were able to measure the one hottest location, we were unable to accurately quantify how many other areas are also crossing this 70°C threshold. Being able to quantify how far is the heat dissipating and how many cells are theoretically

dying can be an aim to further investigate, as larger zones of thermal death, may result in implant failure with certain systems.

5. Small sample size- The results are limited by the small sample size of our study. The data collected and results are limited by the small sample size, and results can be skewed due to only 3 samples per bur. In future studies, a larger sample size is required in order to form more firm conclusions.

7.7 Future Research Directions

While this study provides valuable insights on the way that we consider implant preparation, further research is required to expand on these findings. Future studies should focus on:

- Live bone models- Conducting animal and human clinical trials should be considered to assess real-time biological response to different drill systems.
- Long-term implant success- Examining the correlation between osteotomy temperature and long-term implant survival rates.
- New cooling techniques- Exploring advanced irrigation methods, such as internal cooling systems and bioactive cooling gels, to enhance heat dissipation.
- Examining single- versus sequential-drilling protocols- Different protocols could result in different heat generations.
- Examining multi-fluted drills in counterclockwise direction- to examine heat generated from osseodensification

- Dynamic heatmapping- Being able to see the temperature of all sites in the bone can help us see what is the zone of osteocyte death, and what are the clinical implications of implant healing in larger zones of thermal necrosis.

By continuing to refine our existing drilling protocols and technology, we can hopefully improve the success rates of implants.

VIII. Conclusions

This study confirms that drill design significantly impacts thermal generation, with BCP drills maintaining the lowest temperatures (supporting our null hypotheses). This study also demonstrates that reusing the same drill 3 times does not result in an increase in thermal generation. The findings of this study reinforce the importance of drill selection, proper irrigation, and protocol optimization in minimizing heat-induced bone damage. Future studies should further investigate these variables in clinical settings to optimize implant osteotomy site preparation and improve patient outcomes.

IX. References

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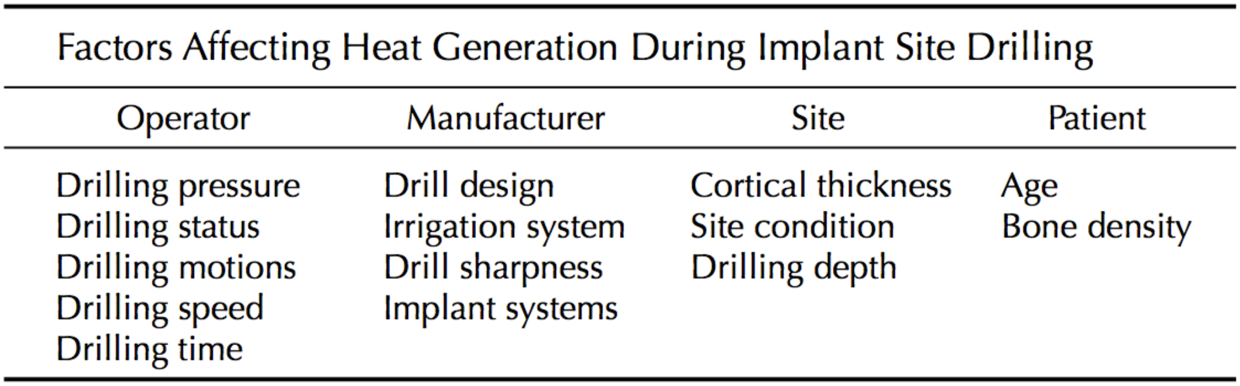
Table 1.1 Factors affecting heat generation during implant bed preparation[1]



Factors Affecting Heat Generation During Implant Site Drilling

Operator	Manufacturer	Site	Patient
Drilling pressure	Drill design	Cortical thickness	Age
Drilling status	Irrigation system	Site condition	Bone density
Drilling motions	Drill sharpness	Drilling depth	
Drilling speed	Implant systems		
Drilling time			

Table 1.2 Bone cell heat shocks from Dolan et al study[16]

Group	Heat Shock
Control	Maintained at 37°C
A	45°C for 30 seconds
B	45°C for 1 minute
C	47°C for 30 seconds
D	47°C for 1 minute
E	60°C for 30 seconds
F	60°C for 1 minute

Table 1.3: Properties of human bone compared to bonesims

Property	Human Cortical Bone	Bonesim
Hardness (Shore D)	85-95	90
Density (g/cc)	1.4-1.9	1.8
Comp. Strength (Mpa)	100-182	110
Screw Insertion Torque (Nm)	1.36-1.58	1.47
Drilling Toughness (s/mm)	2.39	2.42
Thermal Conductivity (W/m/K)	0.3-12.8	0.3–0.4
Specific Heat (J/kg°C)	1260	1200-1300

Figure 1: Areas of Heat Generation on Bur Cutting Edge [18]

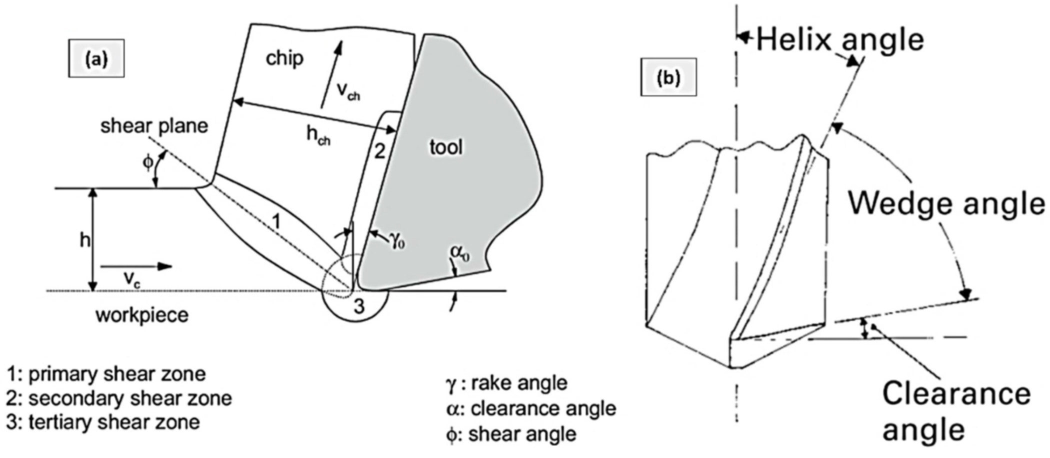


Figure 6. Schematic representation of (**a**) material removal and heat generation regions during chip forming process; (**b**) rake and relief angles [2].

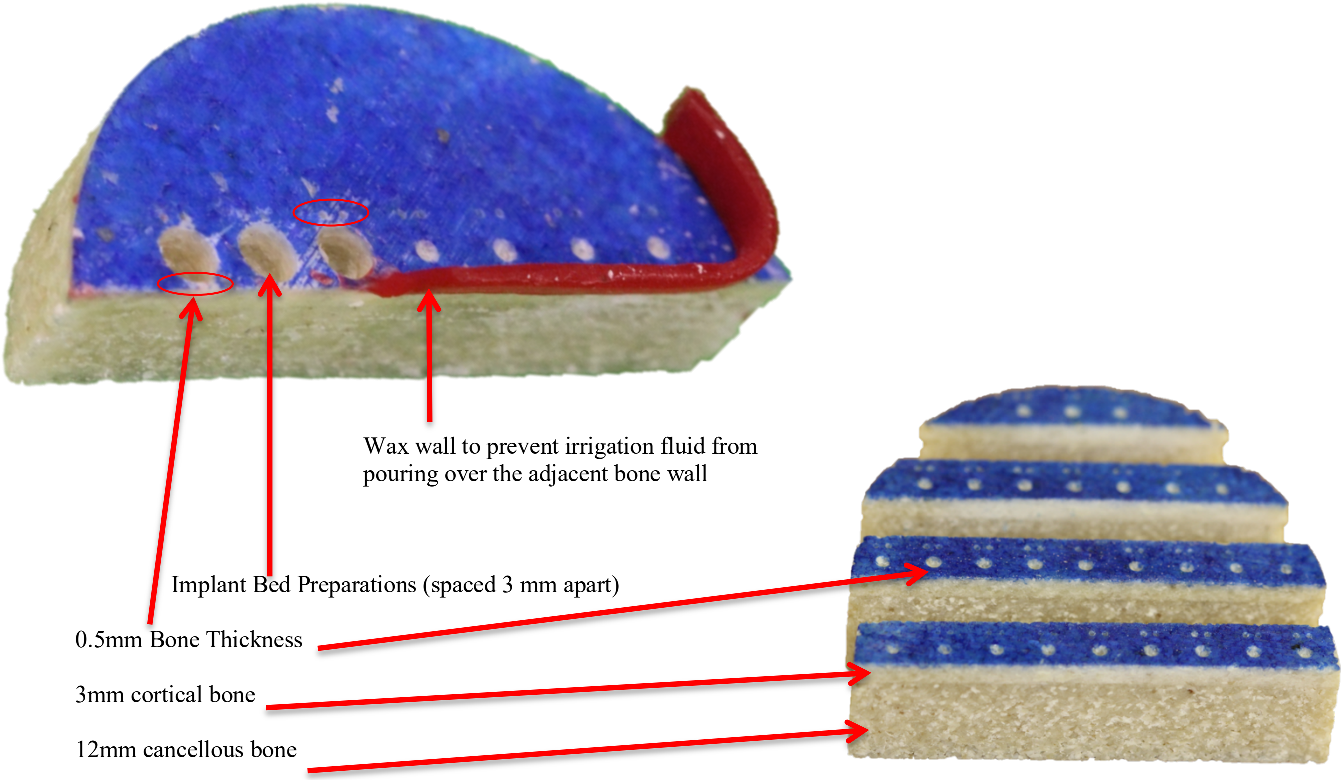


Figure 2.1: CNC machined bonesims

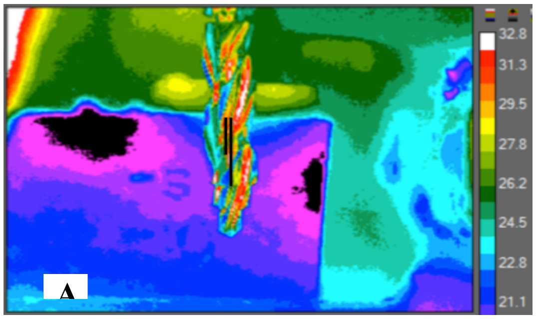


Figure 2.2: Example of how temperature readings during implant bed preparation are collected using the FLIR infrared thermocamera. A still image of 4.2mm diameter surgical drill bit placed in front of bonesim at a depth of 10mm. All drilling procedures begin with such images for proper orientation prior to video analyzations. Average temperature readings are collected over the 10mm implant bed preparation.

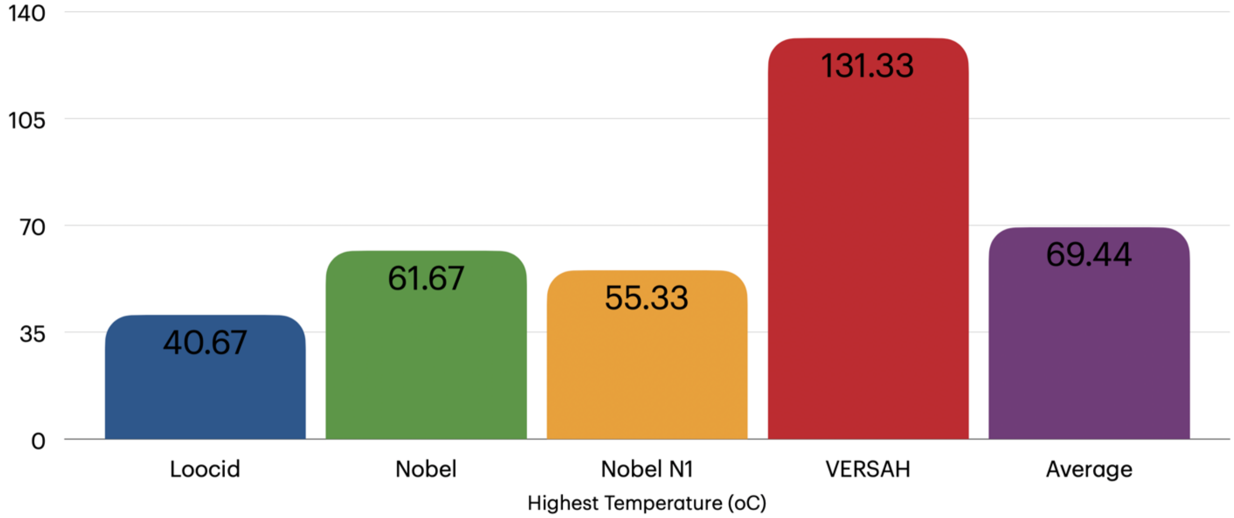
Table 6.1 Statistical results separated by drill group

	Highest Temperature (°C)	Difference in Temperature (°C)	Time for Temperature to Return to Baseline (sec)	Time Above 50 °C (sec)
Loocid	40.67	17.89	111.67	0
Nobel	61.67	36.89	101.11	7.67
Nobel N1	55.33	30.00	78.67	4.33
Versah	131.33	109.00	129.50	12.17
Overall	69.44	40.45	108.44	5.74

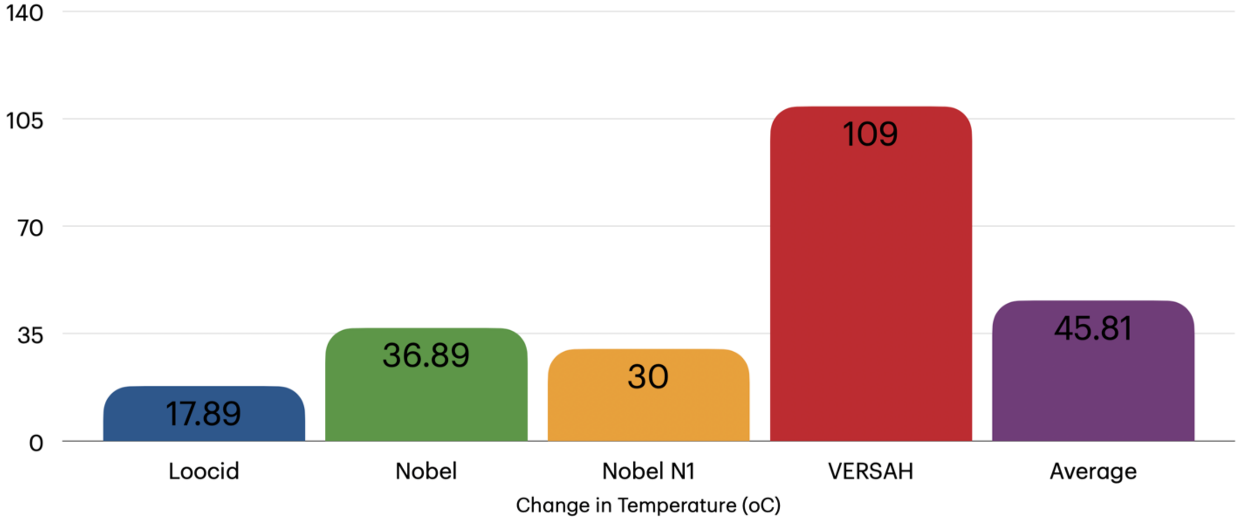
Table 6.2 Statistical results separated by time each drill was used

	Highest Temperature (°C)	Difference in Temperature (°C)	Time for Temperature to Return to Baseline (sec)	Time Above 50 °C (sec)
First Use	67.00	43.44	104.56	7.11
Second Use	67.56	43.44	106.44	3.44
Third Use	73.78	50.56	114.33	6.67

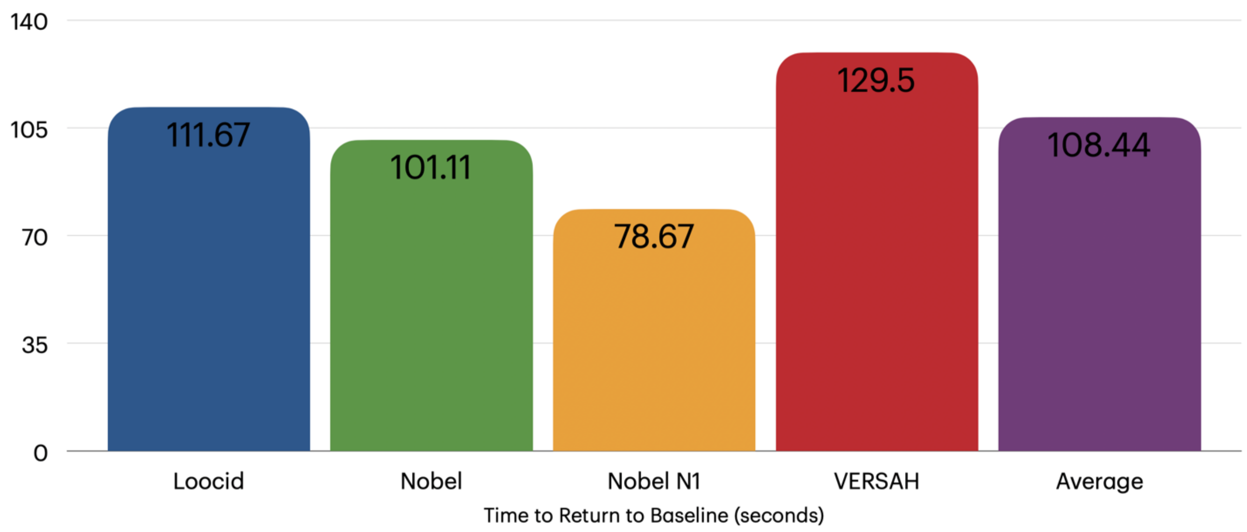
Graph 6.1 Highest Temperatures Reached According to Brand/Type of Bur



Graph 6.2 Change in Temperatures Reached According to Brand/Type of Bur



Graph 6.3 Time to Return to Baseline According to Brand/Type of Bur



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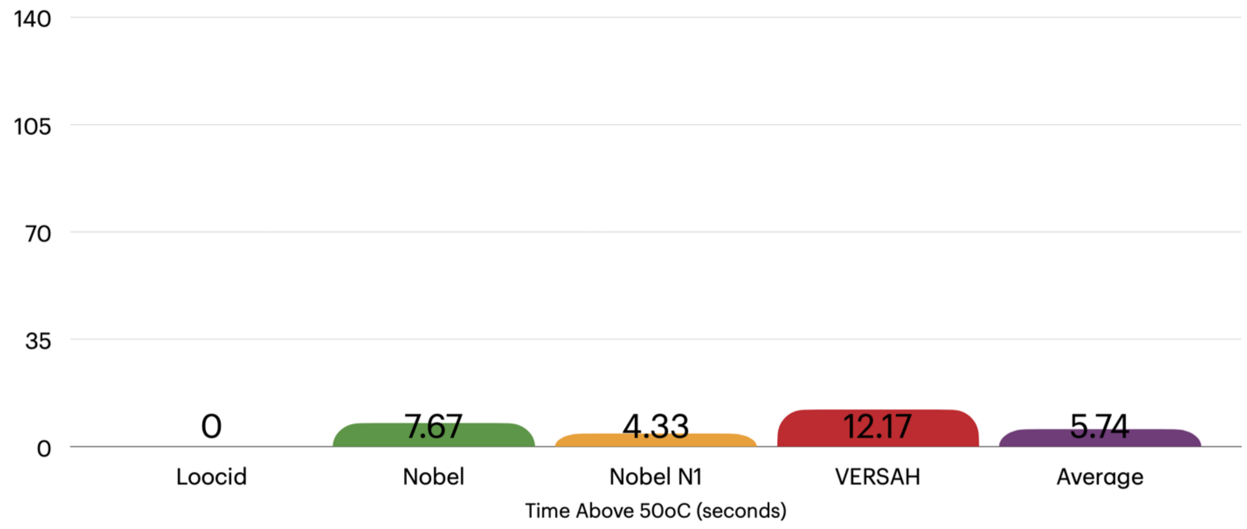
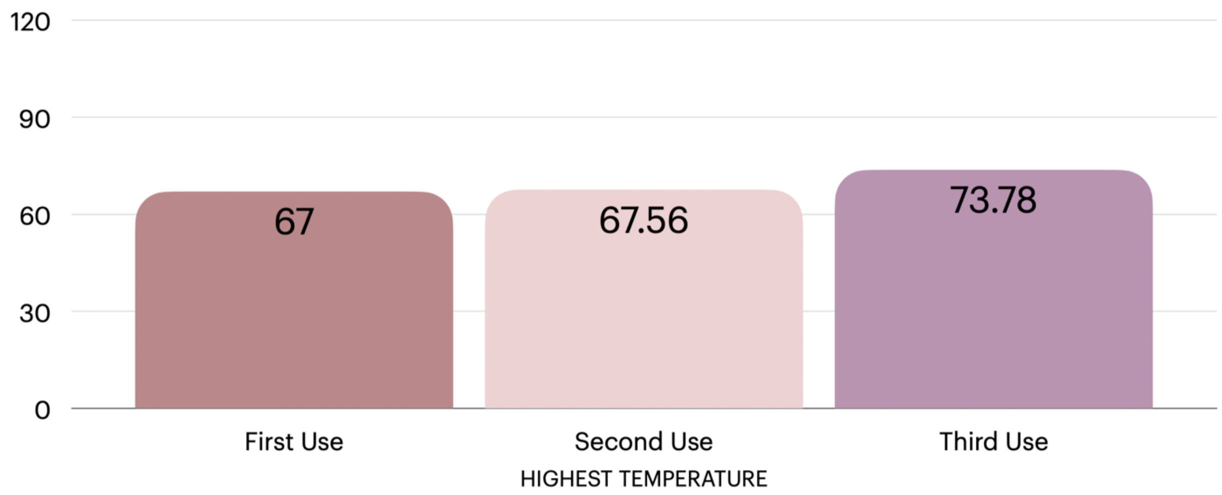
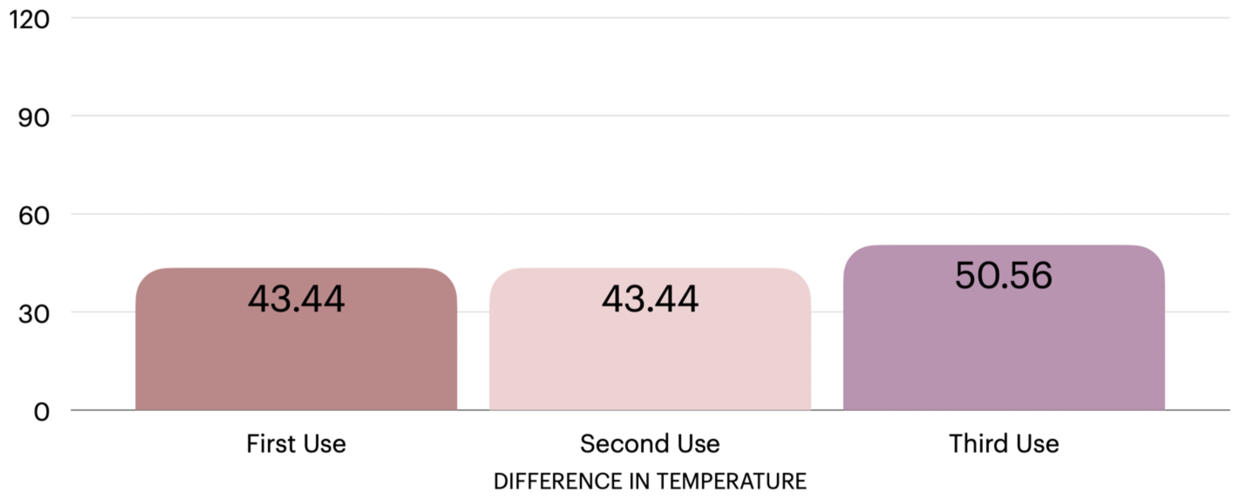
Graph 6.4 Time Above 50°C According to Brand/Type of Bur



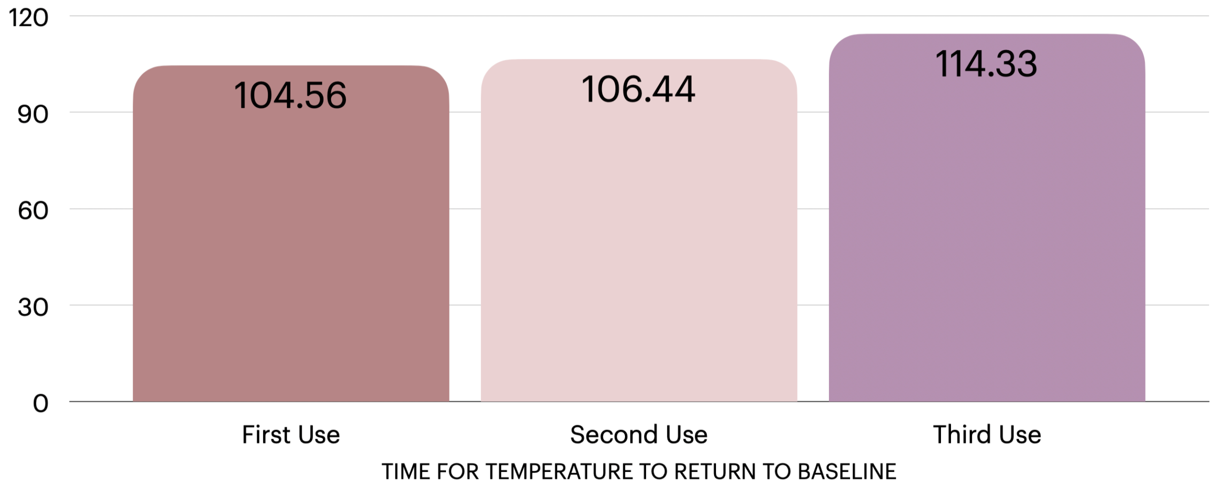
Graph 6.5 Highest Temperatures Reached According to Use



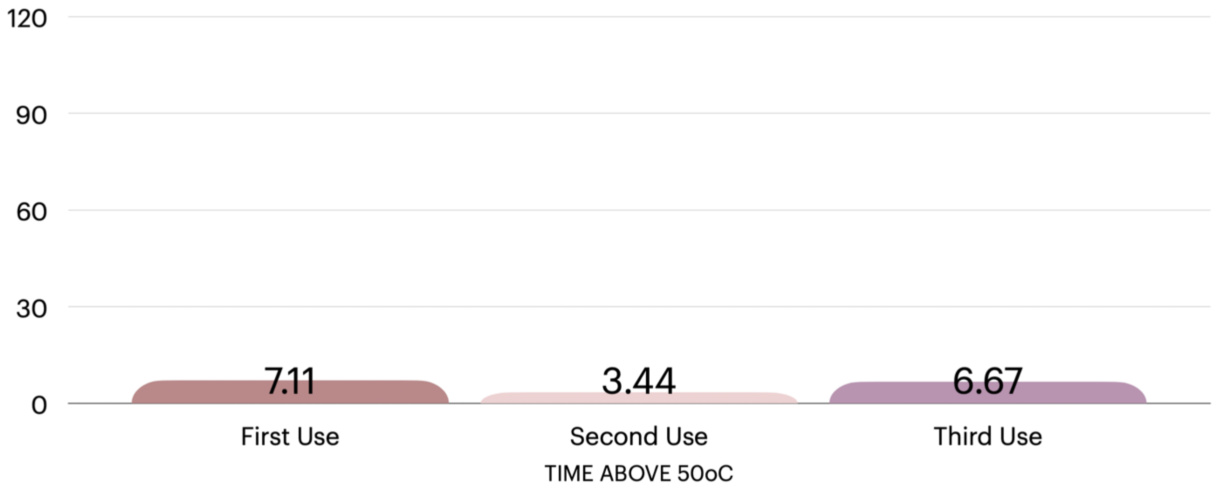
Graph 6.6 Difference in Temperatures Reached According to Use



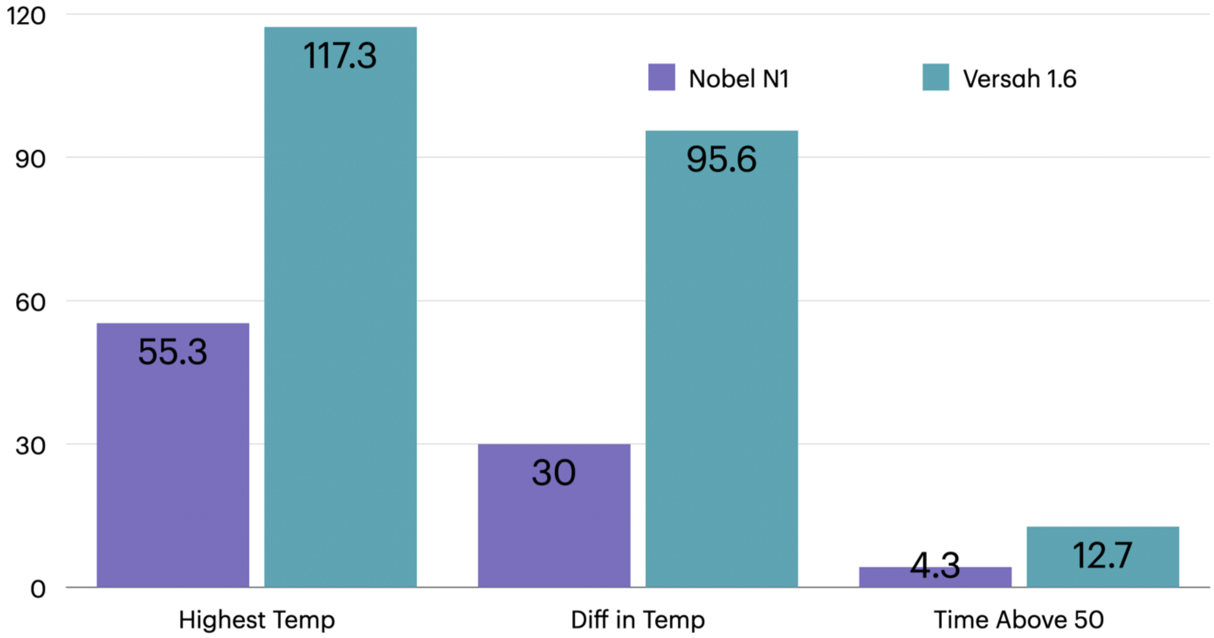
Graph 6.7 Time for Temperature to Return to Baseline According to Use



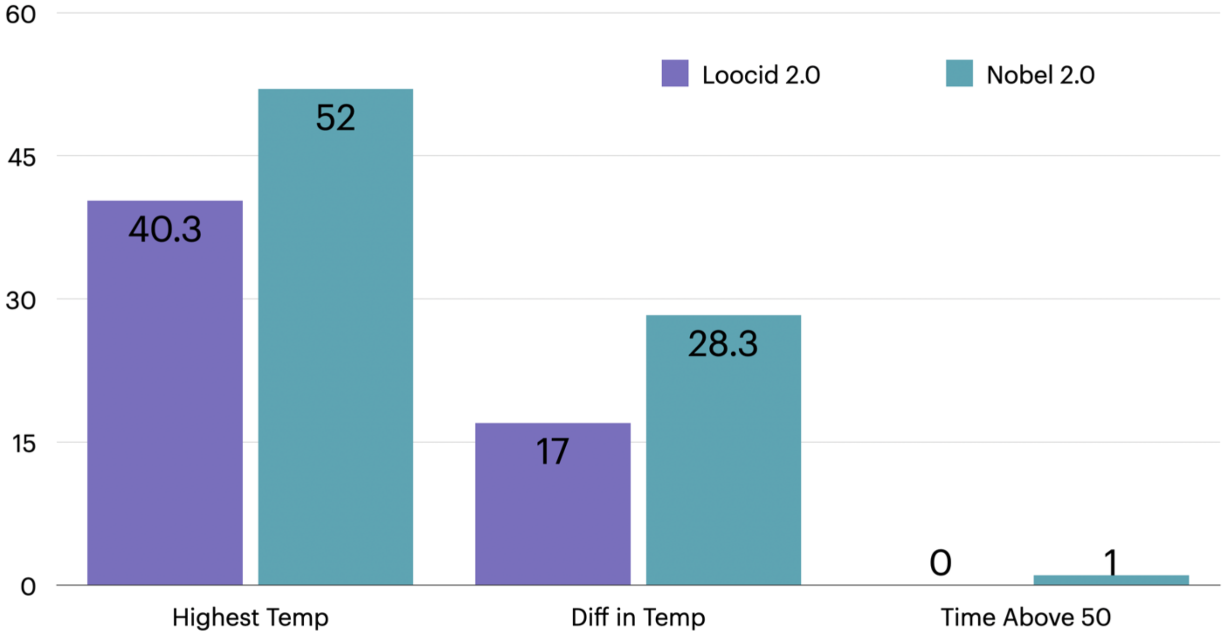
Graph 6.8 Time Above 50°C According to Use



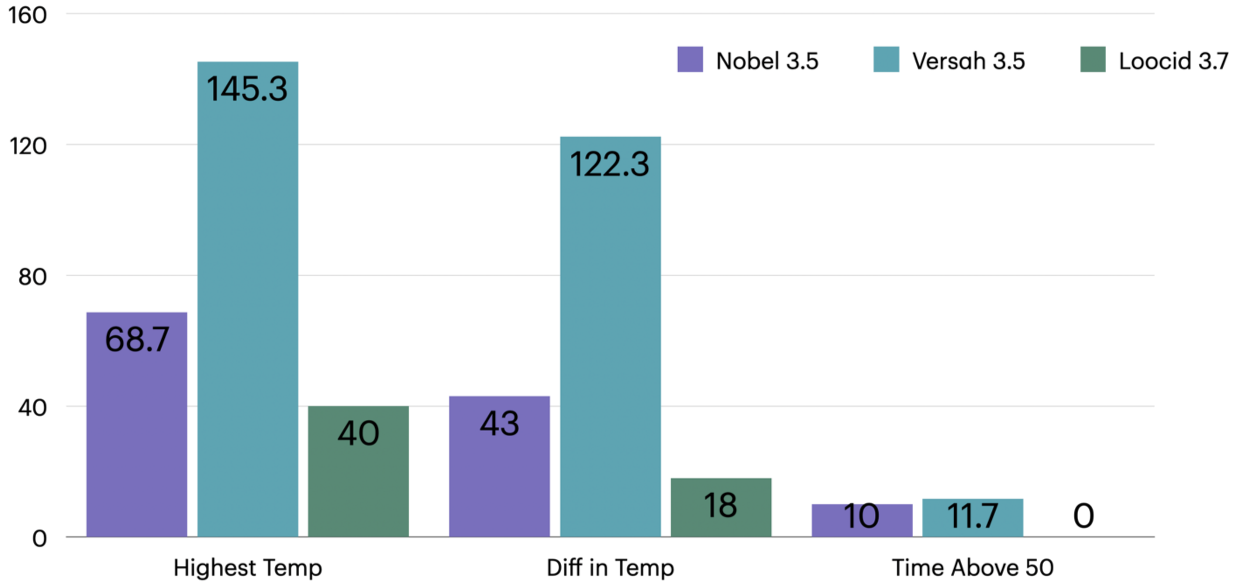
Graph 6.9 Comparison of ø1.6 and ø1.8 Diameter Burs



Graph 6.10 Comparison of ø2.0 Diameter Burs



Graph 6.11 Comparison of ø3.5 and ø3.7 Diameter Burs



Graph 6.12 Comparison of ø4.2 and ø4.3 Diameter Burs

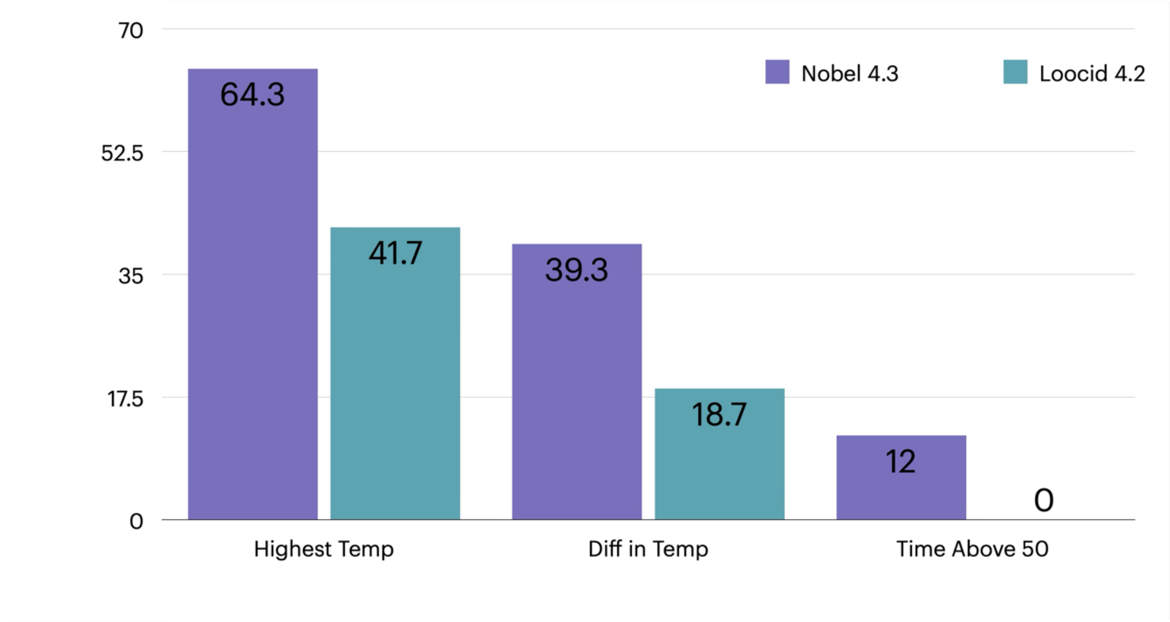


Figure 7.1 Areas of Drill Wear[18]