Temperature Changes (ΔT) in Correlation with Number of Implant Osteotomy Preparations in Human Cadaver Tibiae, Comparing Osseodensification (OD) Burs in Clockwise (CW) versus Counterclockwise (CCW) Mode

Amanda Heydari, DDS

Oregon Health and Science University (OHSU)

Advanced Education in Periodontics

ACKNOWLEDGEMENTS

I would like to express my gratitude to my principal investigator and mentor, Dr. Soldatos, for his guidance, support, and contributions to this project. This project has been the continuation of a series of ongoing studies, and I am grateful to have been a part of the research associated with this subject. His encouragement and direction have been paramount to my experience and getting this project completed.

I'd like to thank my committee members, Dr. Stathopoulou, Dr. Katancik, Dr. Weltman, and Dr. Choi for their knowledge, expertise, and advice in this project. In addition, I'd like to express my appreciation to my cohorts Dr. Horton, Dr. Sarrami and Dr. Nordlie, as they gave their time and aid and have been monumental in the completion of this project.

I'd like to thank the staff at VirtuOHSU for their assistance in supplying us with space and supplies for this project. Their continued assistance and flexibility throughout a difficult time and unexpected winter storm allowed us to continue with getting our data collection completed.

Lastly, I'd like to thank donors for donating their body to science, and the families in support. Without them, this project could not have been completed. I have the utmost respect for those who, after their time here, continue to give back to the world in the name of science and research.

Table of Contents

CHAPTER 1

Literature Review

INTRODUCTION

The first concept of dental implants dates to 2500 BC in ancient Egypt. These implants were made of gold, animal bones, or ivory-fashioned with ligature wire to replace missing teeth. The first evidence of dental implant is attributed to the Mayan's dating back to around 600 AD in which pieces of shells were inserted into the mandible to replace anterior teeth. Around 800 AD in Honduras, stone implants were prepared and placed in the mandible.[1]

Between the 1500's and 1800's teeth were collected from the underprivileged and cadavers for allotransplantation, as well as innumerable substances like silver capsules, gold implant tubes, corrugated porcelain and iridium tubes to be used as implants. The 1900's were really the forefront of implant development. During this time, implants of platinum-iridium soldered with 24 karat gold and orthopedic screw fixtures made of vitallium (chromium-cobalt alloy), modeled after implants placed in the hip, were being used to restore individual teeth in humans and dogs. The Strock brothers were thought to be the first to place the first successful endosteal implant, modeling their methods after their physician counterparts. Following this, stainless steel, chromium cobalt, and aluminum implants with different designs, such as spiral threads, flat abutments over the ridge fixed with screws, blade implants, and transosteal implants were fabricated to test their success and survival.[1]

As we move into modern-day dentistry, the osseointegration and success of dental implants began as an incidental finding by Brånemark in 1952 while studying blood flow related to bone healing in rabbits. He placed titanium chambers in their femurs and after some time of healing, when he went to remove them, the titanium chambers became firmly affixed to the bone, making them unable to remove. The titanium and bone were bonded together.[2] This sparked further research into this concept of "osseointegration" after a period of healing and was carried into the field of dentistry. Osseointegration is defined as a direct—on the light microscopic level—contact between living bone and an implant.[3] The difference between the success and survival of the implants seen with Brånemark's studies compared to those who came before him was the osseointegration of these titanium chambers.

The question of why implants fail to osseointegrate is an ongoing topic within the research of implant dentistry. Implant failure is defined based on the time in which the failure occurs. Early implant failure is defined as implant failure within the initial stages of healing, either before or after abutment connection. This is due to a failure of the implant to osseointegrate during the first few months following implant placement. Late implant failure is defined as failure to maintain the established osseointegration due to a process involving its breakdown.[4] This occurs after occlusal loading and is usually accompanied by severe bone loss. Although the mean implant survival rate is around 94.4%, there is a small but relevant implant failure rate of less than 10% .[5] Some of the risk factors associated with implant failure are procedural factors, poor bone quality, chronic periodontitis, systemic diseases, smoking, genetics, implant location, parafunctional habits, loss of implant integration and inappropriate prothesis.[4, 5] Many of these factors have been studied and documented, while others are not well understood.

When looking at early implant failures, providers must look at potential procedural factors that may contribute to the implant not being successful. Based on their specific designs, each implant system has a recommended protocol for preparations of implant osteotomies. This usually involves specific revolutions per minute (RPM) in which they are recommended to be used to decrease friction generation, which may result in increased temperatures and devitalization of the surrounding bone. The speed of the drill and the process of consecutive osteotomies drilled to widen the planned site of the implant generate heat. Copious irrigation with sterile saline is part of standard protocol in attempts to reduce the amount of heat that is generated. Many studies have reported that temperatures more than 47°C for 1 minute can lead to thermal injury and possible osseous necrosis.[6-9] This necrosis of the surrounding bone at time of implant placement can result in connective tissue encapsulation and early implant failure.

Not only does the speed of the drill have an effect, but the design of the burs can also contribute to the amount of frictional heat that is generated. Osseodensification burs have been designed to be used in either the clockwise (CW) or counterclockwise (CCW) direction, depending on the desired purpose. Using the burs in the CCW direction will rotate the burs in a high-speed, non-cutting direction and will densify the bone (osseodensification-OD). Using the burs in the CW direction will cut the bone (cutting mode).[10] Given that this drill is designed to be used in both clockwise and counterclockwise directions for different purposes, the physiologic changes of the surrounding area may also be different.

Current literature on implant dentistry and temperature changes related to current implant osteotomy drilling protocols discusses the risk of alveolar bone loss due to thermal necrosis. With the advancement of different dental implant products, implant designs and clinical procedural guidelines, the need for continuing assessment and research on these products and clinical protocols is necessary for evidence-based clinical decision making. This project, modeled after our group's previous studies[11-13], aims to provide information regarding the temperature changes related to OD burs, in both OD and cutting mode at different RPM. The null hypotheses for this project are:

1) CW/CCW use of OD burs for dental implant placement will produce the same amount of heat in bone at every RPM.

2) Using the burs 20, 40 and 60 times will result in the same amount of heat generation in every RPM and mode.

MATERIALS AND METHODS

An electronic literature search of online databases including PUBMED and Google Scholar was completed using combinations of the following combinations of keywords: “dental,” “implant,” “osseodensification,” “densify,” “osteotome,” “drill,” osteotomy,” “heat,” “heat generation,” “temperature,” “thermal damage,” “thermocouple,” “pressure,” “compression necrosis,” “force,” “drill speed,” “RPM,” “drill design,” “drill diameter,” “drill wear,” “drill width,” “drill depth,” “vibration,” “chatter,” “bone density,” “cortical thickness,” “irrigation,” “1-step drilling,” and “clogged drill flutes.” Studies from 1969 to 2023 were evaluated and deemed appropriate for review. Studies that were not relevant to dental implants were excluded.

DISCUSSION

Primary biomechanical stability of dental implants is of paramount importance for osseointegration of dental implants and long-term success as well as in avoiding connective tissue fibrous encapsulation of the implant.[14] Increasing primary stability can be completed in a number of ways, including OD or through an adaptive osteotomy protocol (AO), in attempts to achieve direct contact between bone and the implant.[10, 15, 16] Threaded implants are designed when inserted to create maximal contact between bone and the implant surface. This close relationship between the bone tissue and the implant forms the morphological substrate for good mechanical stability, minimizing early implant movements and increasing implant success.[3, 17] The quality and quantity of the bone at the implant interface is correlated to the bone density.[18]

By preserving as much bone as possible, we increase the bone-to-implant contact (BIC) as well as the density of the bone, accelerating the healing process after surgery with accelerated osteoblastic activity.[10, 19] This was seen in Yeh’s animal model on bovine ribs, when an OD protocol was used. The peripheral BIC percentage and mineral density around the implants was significantly higher in the OD group as compared to the conventional drilling protocol.[20] When comparing OD to conventional drilling, osteotomes and piezo surgery, Bhargava showed in their porcine rib model the highest insertion torque with the OD protocol.[21]

Osteotome technique

The osteotome technique, first pioneered by Dr. Hilt Tatum, and then later described by Summers in 1994, is a minimally invasive, crestal approach to sinus elevation using osteotomes—a method that allows implant placement in the posterior maxilla with limited residual bone height, without the need for a lateral window. Osteotome technique is used to compact and densify the bone, as well as in vertical sinus elevation procedures. It is performed by using a series of expanders and a mallet to advance the osteotome, and in performing vertical sinus elevation, to infracture the maxillary sinus floor.[22] This technique has been shown to increase the primary stability of implants at time of placement but may not make a difference in the long-term stability after the osseointegration period.[23, 24] Some of the limitations of this technique include repeated use of the mallet, which may be traumatic for the patient and can be difficult to control. Additionally, patient side effects such as benign paroxysmal positional vertigo secondary to calcium carbonate crystals of the inner ear getting dislodged during the repeated tapping of the mallet have been reported.[25]

Adaptive osteotomy

Adaptative osteotomy protocol is completed by under-sizing the implant osteotomy by one full drill size or in the apical portion only by preparing the top half of the osteotomy to the final drill diameter.[15, 26] The implant is then placed in this undersized osteotomy, increasing the surface area of BIC, decreasing the implant micromotion, and increasing the primary stability. This technique can be applied to different clinical situations depending on the density of bone intraoperatively.[16, 20, 27, 28] A study by Capparé prepared a 2.3 mm osteotomy preparation and then placed a 3.3 mm implant with a corresponding torque value and bone density measurement. The implant was left in place for 15 minutes to allow for the bone to adapt via its elastic response. A trephine was then used to remove the implant and 0.5 mm layer of surrounding bone. This study found that increased BIC correlated with increased torque values and bone density.[29] The previous study found increased BIC at time of implant placement with an undersized osteotomy preparation, but whether that BIC remains or changes after initial healing requires evaluation after the osseointegration period. Shalabi et al. compared press-fit (osteotomy diameter=implant diameter) osteotomy preparation to the undersized osteotomy preparation and the osteotome preparation after 12 weeks of healing. This study found increased BIC in the undersized osteotomy preparation- 38% in etched implants and 24% in machined implants compared to 28% and 20% in press-fit osteotomies.[30] Another study by Shalabi et al. found the highest mean torque values among removal of osseointegrated implants when placed by the undersized approach.[31]

Osseodensification (OD)

A newer technique for bone preservation has been developed via OD burs. The burs are specifically designed with a tapered design, large negative rake angle, and noncutting edges. The burs are designed with cutting, chiseled edges to develop the osteotomy depth, and a tapered shaft with non-cutting edges to compact the bone laterally creating a layer of compacted autogenous bone along the surface of the implant osteotomy while increasing the osteotomy diameter. When used in a CCW rotation (OD mode) with the aid of hydraulics, it allows for compaction of the bone into the osteotomy preparation, similar to a tornado in bottle. With a pumping motion, the irrigation is forced towards the tip of the bur, inducing a pressure wave, forcing autogenous bone particles into the trabecular spaces of the inner walls of the osteotomy. When run in a CW mode, the burs cut and extract the bone from the osteotomy preparation.[10] These burs can be used for ridge expansion, molar septum expansion, crestal (vertical) sinus augmentation, immediate and zygoma implants. Histologic evaluation of the osteotomy shows new bone formation on the bone chips embedded in the walls of the osteotomy and a higher ratio of new bone to autographed/native bone when compared to conventional drilling. Additionally, these burs in both modes outperformed conventional drilling protocols when looking at torque values, BIC, and bone-area-fraction occupancy (BAFO).[27] The hepatic feedback of the bur and bone density allows for the provider to control the force applied to the bur during preparation, aiding in a more controlled preparation[10]. This is important especially during vertical sinus augmentation and aids in increased control and decreased risk of adverse events such as sinus membrane perforation.

Huwais et al. found approximately double the insertion torque values of 4.1 mm and 6.0 mm implants with osteotomy preparations using the OD burs in OD mode as compared to the standard or extraction drilling technique. There was also more than double the removal torques of the standard extraction drilling technique. OD technique osteotomies had a layer of compacted bone with increased bone mineral density along the wall of the osteotomy compared to constant bone mineral density around osteotomies created through drilling.[10] Romeo et al. evaluated the use of OD burs compared to conventional burs in CW and CCW modes at 600 RPM. They evaluated how the different modes related to implant stability as a measurement of both insertion torque and resonance frequency analysis. OD burs in CCW mode allowed for significantly higher insertion and removal torque. Additionally, the osteotomy created with the OD burs in CCW was narrower than conventional drilling, as described as the spring-back effect by Kold et al.[28, 32, 33] The spring-back effect, reported by Huwais et al. in a porcine tibial model, is due to the viscoelastic portion of deformation which causes a 91% reduction in the osteotomy size after OD.[10]

Bone Model Characteristics

Cortical Thickness

Different models have been used in literature to discuss cortical thickness including animal models on tibias, femurs and ribs, as well as in human models using mandibles, maxillas, tibias, and femurs. Other models include bone substitutes made from polyurethane bone. [2828] Many studies on temperature changes (ΔT) during drilling do not report on cortical thickness. A summary of the average cortical thickness of different bone models in the literature is in Table 2.

Initial thermal studies evaluating temperature of bone during osteotomy preparation were completed using animal models. These studies were completed on hare and rabbit models as well as dog models and humans, using the femur or tibia. Cortical thicknesses ranged from 1.5 mm in rabbits to 3.5 mm in dogs and 6.5 mm in humans.[34]

A study by Ono et al, used CBCT to evaluate buccal cortical thickness in the posterior mandible and maxilla for placement of orthodontic mini-implants. The average cortical bone thickness ranged from 1.09 to 2.12 mm in the maxilla and 1.59 to 3.03 mm in the mandible. The greater the height, the thicker the cortical bone tends to be. The cortical bone was significantly thicker in the mandible than in the maxilla, and thinner in female than in males in the region medial to the first molar.[35] This study doesn't provide much information regarding the thickness at the crest where implants are placed, and bone loss is mostly seen.

Katranji et al. completed a human cadaver study evaluating cortical bone thickness in various regions of maxilla and mandible. Their findings based on 28 cadavers included that the average buccal cortical thicknesses were 1.69 mm (molar), 1.43 mm (premolar) and 1.04 mm (anterior) in the edentulous maxilla; 2.06 mm (molar), 1.78 mm (premolar) and 1.36 mm (anterior) in the edentulous mandible; 2.23 mm (molar), 1.62 mm (premolar) and 1.59 mm (anterior) in the dentate maxilla; and 1.98 mm (molar), 1.20 mm (premolar) and 0.99 (anterior) in the dentate mandible. This study measured the alveolar crest and 3 mm apical to the crest. In edentulous areas, the crest was ground down 3 mm under the pretense that crestal resorption is a common phenomenon post-extraction and where the crestal third of an implant is located.[36] The assumption that crestal resorption has not already occurred in this edentulous space presents a limitation in their study design. Additionally, this measurement can be applied to the thickness of the buccal plate but does not report on the thickness of the cortical bone on the crest, similar to findings by Ono et al.

In aim to evaluate the thickness of crestal bone in edentulous sites, Ko et al. evaluated CBCT images from 173 patients. This study found that crestal bone thickness was greatest in the posterior mandible (1.07 ± 0.47 mm) followed by the anterior mandible (0.99 ± 0.36 mm), anterior maxilla (0.82 ± 0.30 mm) and finally the posterior maxilla (0.75 ± 0.35 mm).[37] This study described lower cortical thickness compared to other studies. Miyamoto et al. and Gerlach et al. measured a cortical thickness of 2.22 ± 0.47 mm, and 2.00 ± 0.15 mm respectively in the mandible.[38, 39] There is a wide range of cortical thickness between subjects, related to location as well as ethnicity and age.

In a study by Maeda et al., the average cortical thickness, evaluated by clinical computed tomography (CT), ranged from 6.2 to 11.3 mm in young men, 4.2 to 9.3 mm in young women, 5.3 to 8.9 mm in elderly men, and 4.8 to 7.6 mm in elderly women. They found no sex-related statistically significant differences in all 12 regions of the tibia although there was a greater trend of greater cortical thickness in elderly men in the anterior and posterior areas, and greater cortical thickness in elderly women in the medial and lateral areas.[40]

Modulus of Elasticity and Compressive Strength

Modulus of elasticity is a property of a material in which it can resist deformation under pressure. The higher the modulus of elasticity, the stiffer the material is. Compressive strength measures the resistance of a material to break under compression. Goldstein et al. reported the modulus of elasticity in the human tibia ranged from 4.2 MPa in the center to 430 MPa in the load bearing areas, where Larsen et al. found the modulus of elasticity to range from 14 to 345 MPa.[41, 42] Misch et al. reported the modulus of elasticity of the mandible to range from 24.9 to 240 MPa. Additionally, Misch found the compressive strength of the mandible ranged from 0.22 to 10.44 MPa with a mean value of 3.4 MPa, where Burstein et al. found the compressive strength of the tibia to range between 1.08 to 1.24 MPa.[43, 44] The findings from these studies show similar characteristics of the human mandible and the human tibia and serve as a basis for the human tibia as a translational model for research data collection in reference to dental implants.

Porosity and Mineralization

The porosity of bone is the volume fraction of bone that is not occupied by bone tissue. It is considered to be inversely proportional to bone strength and stiffness. More heavily loaded bone has been considered to have a higher remodeling rate and is therefore less mineralized and less stiff than bone that is less loaded. Cortical bone remodeling occurs by the formation of osteons, where bone is deposited near the surface of the cortical canals and therefore is younger and less mineralized. Trabecular bone remodeling occurs at the trabecular surfaces and therefore the surfaces are generally less mineralized. Cancellous bone has been considered to have a higher turnover rate, most likely due to the larger surface area for osteoblastic and osteoclastic activity. Cortical bone has been shown that an increase in porosity coincides with a decrease in mineralization. To evaluate these findings, Renders et al. evaluated the degree of porosity and mineralization of the cortical and trabecular bone of the high loaded human mandibular condyle under microCT. This study found that the average porosity of cortical bone was 3.5% as compared to 79.3% in trabecular bone.[45] This relates to the quality of bone during implant placement. Lekholm and Zarb described 4 types of bone. Type I is a homogeneous compact bone. Type II is thick cortical bone surrounding dense trabecular bone. Type III is thin cortical bone surrounding dense trabecular bone, and Type IV is thin cortical bone surrounding low-density trabecular bone. This description was intended to aid providers in predicting implant stability and success.[46] This was substantiated by the systematic review by Gioato et al. which showed the relative average implant survival rate in different bone types; 97.6% for type 1, 96.2% for type II; 96.5% for type III; and 88.8% for type IV.[47] This systematic review highlights the critical role of bone quality in the long-term success of dental implants and underscores the value of optimizing bone conditions intraoperatively through various osteotomy preparation techniques.

Temperature Evaluation

Most literature uses thermocouples for measurement of temperature during implant osteotomy preparation, while others use infrared thermography.[7, 8, 34, 48-52] Both methods have been shown to be accurate; however, infrared thermography is an indirect measurement of temperature based on the heat radiating from the surface. Additionally, infrared thermography does not produce accurate readings if measurements are taken through liquids or glass[53], which may affect temperature measurements when osteotomy preparations are completed with irrigation.

An in vivo study by Flanagan et al. used a thermocouple encased in a closed hypodermic needle to sheath the end of the thermocouple, while attempting to measure whether irrigation is necessary in preventing increased temperatures during osteotomy preparation. The thermocouple and needle were placed in a 10 mm deep osteotomy preparation 2 mm from the center of the implant osteotomy site to measure the bone near the osteotomy preparation. As the implant osteotomy preparation increased, it approached the proximity to the thermocouple sensor, but did not make contact. The results of this study showed that there was no temperature elevation during preparation.[49] This study design presents a significant limitation which is present in most of the previously reported studies, in that the temperature was never recorded inside the actual osteotomy preparation.

Most of the studies on temperature evaluation have been completed using a thermocouple that was placed in a separate osteotomy with variant ranges from the osteotomy preparation, ranging from 0.5 mm to 2 mm.[8, 34, 54-58] Although this study design for temperature measurement has been widely used, the temperature of the wall directly inside of the osteotomy preparation is not being measured with this method of evaluation, potentially underestimating the temperature measurements along the osteotomy wall. There has been shown that measurements 0.3 to 0.5 mm from the osteotomy can have a 1.5° C temperature difference.[59] Matthews et al. found that the highest temperatures occur 0.5 mm from the osteotomy, which rapidly decreases with distance. Beyond 2 mm the temperature changes were negligible. This emphasizes a significant limitation in this type of temperature assessment.[56] Additionally, the added layer of the hypodermic needle sheathing for the thermocouple sensor in the study by Flannagan et al. may act as a barrier to detect the temperature of the bone. This study was designed the way it was due to the inability to sterilize the thermocouple after intraoral use. Given this limitation, the use of the thermocouple prevents data collection from being completed in live patients when measuring directly on bone.

Surgical Trauma

Peri-implant bone loss during the initial healing period is linked to surgical trauma during implant osteotomy preparation.[9, 60, 61] By reducing this surgical trauma, we can decrease the risk of early bone loss during this initial healing period.

Compression Necrosis

The crestal bone around an implant is comprised of dense cortical bone with minimal vasculature, making it more susceptible to ischemia and damage to osteocytes theoretically resulting in necrosis when under high load or excessive strain. Inserting implants at high torque values may induce necrosis. Some studies show that implant success rates are inversely proportional to high insertion torque values.[17] Compression necrosis has been reported in case reports as a possible etiology for unknown reasons of crestal bone loss during initial healing after implant placement at high torque values.[62, 63] This theory has not been proven as a definitive explanation for early crestal bone loss however, and other studies have made attempts at disproving this theory. Trisi et al. showed in an animal model where implants placed in dense cortical bone at 110 Ncm compared to those placed at 10 Ncm, had higher removal torque values and did not result in early implant failure or bone necrosis. The crestal bone at high torque insertion values however did undergo significantly more remodeling and replacement with new woven bone compared to the low insertion torque group.[64]

Bone Thermal Injury

The critical threshold for temperature of bone during drilling was first described by Eriksson and Albrektsson in rabbits. A thermal chamber was inserted into the tibia and heated 10 weeks after it was inserted. A thermocouple was inserted into the canal of the chamber to be in direct contact with the bone. The chamber of bone was subjected to temperatures of 50° C for 1 minute, 47° C for 5 minutes and 47° C for 1 minute, and the tissues were evaluated via vital microscopic imaging. Hyperemia was noted during heating by 40-41° C. By 50° C blood flow stasis was noted in some minor blood vessels. No short-term connective tissue injury was noted in the first two hours after thermal injury; however, long-term effects were noted on average 40 to 60 days after injury. This included fat tissue resorption, which peaked at 2 weeks, followed by a fat cell invasion of 150% to 200% increase in the groups that were heated to 50° C for 1 minute and 47° C for 5 minutes. This was not seen in the group heated to 47° C for 1 minute. Bone remodeling was noted 20 to 30 days following thermal injury in groups heated to 50° C for 1 minute and 47° C for 5 minutes, resulting in 30% to 40% less bone compared to initial. In the group heated to 47° C for 1 minute, most of the animals resulted in minor bone resorption which was difficult to separate from normal bone remodeling. The conclusions from this study show that 47° C for 1 minute is the critical temperature threshold level for bone survival.[7,9] This was further substantiated in Eriksson and Albrektsson's follow up studies in which even with irrigation, temperatures may rise above this critical threshold and result in vascular injury and thermal injury to the bone.[8, 34]

Trisi et al. in an animal study on the iliac crest of sheep, heated some osteotomy sites to either 50°C for 1 minute or 60°C for 1 minute using a hot probe prior to implant insertion. When compared to the control, the sites heated to 50°C for 1 minute showed no statistically significant difference in BIC percentage. Significant differences in BIC percentage were found however, when the bone was heated to 60°C for 1 minute when compared to the control. These implants were also associated with significant differences in infrabony pocket depth in the group heated to 60°C as well as crestal bone resorption compared to the control.[65]

Factors Affecting Heat Generation

There are a number of factors that have been reported to affect heat generation during implant osteotomy preparation.[11, 13] Factors that may influence the bone overheating are pressure applied, bone density, drilling sequence, drill design, irrigation type, and overused/dull burs. The reviewed and referenced studies, including their designs and findings, have been summarized in Table 1. Factors related to the operator, the patient, or the implant drills are outlined in Table 3.

Intermittent Cutting Motion

The technique in which the implant osteotomy is created can be altered in a number of ways. One of which is whether the applied pressure is continuous or intermittent. The idea is that with intermittent pressure, the provider can decrease the amount of friction created between the bur and the bone, in turn decreasing the amount of heat generated. Gehrke et al. evaluated whether more heat was generated with continuous drilling compared to intermittent drilling. There were two controls and two test groups- (CG1) external irrigation and continuous movement, (CG2) external irrigation and intermittent movement, (TG1) double irrigation and continuous movement, and (TG2) double irrigation and intermittent movement. The temperature was evaluated with a K-type thermocouple 0.5 mm from osteotomies on bovine ribs. The results of this study found a significant difference in temperature increase between intermittent vs continuous movement— 1.72° C vs 3.07° C respectively.[55] Ercoli et al. found similar findings, with a few osteotomies reaching above the critical threshold when a continuous cutting movement was used.[66] Conversely, Di Fiore et al. compared continuous drilling with intermittent drilling in bovine ribs under irrigation at 1200 RPM, and they found no difference in temperature related to the two different drilling methods.[67] This study measured temperatures 5 mm from the preparation, which may have impacted the accuracy of the temperature readings directly adjacent to the osteotomy preparation.

Applied Pressure

About 2 kg force (kgf) is the commonly applied pressure exerted during osteotomy preparation[68]. The force or applied pressure to the handpiece while preparing the osteotomy has the potential to increase the friction generated and could have an effect on the temperature of the surrounding bone.[69] Raj et al. evaluated two forces 1.2 kgf and 2.4 kgf during preparation at 1500, 2000 and 2500 RPM under room temperature saline and chilled saline external irrigation on bovine femur. The temperature was evaluated using infrared thermography. This study found that the highest temperature was observed at 2000 RPM, 1.2 kgf pressure, and room temperature irrigation. The lowest temperature generated was using 2500 RPM, 2.4 kgf hand pressure, and chilled irrigation. None of the experimented parameters generated heat above the critical threshold for bone necrosis.[70] Similarly, a study by Matthews et al. found that higher drilling forces were associated with a lower average maximum temperature and shorter duration of temperature elevation.[56] It is possible that increased force decreases the amount of time it takes for drilling, which in turn decreases the time the bone is under frictional heat. Additionally, a higher speed of rotation may accommodate the increased pressure applied to allow for more efficient cutting. Other studies have failed to show a statistically significant difference in temperature at pressure load of 0.8 kg, 1 kg, 1.5 kg, and 2.0 kg at various RPM.[57, 58, 68, 71]

Cortical Thickness

As previously described, the thickness of cortical layer of bone in an implant osteotomy site can vary greatly from person to person but also depending on the surgical area. Lamazza et al. evaluated the heat generated in different cortical thicknesses in both bovine cortico-cancellous ribs and cortical only samples of bovine femur. Osteotomies were prepared under 150 gr load with a diamond tip piezoelectric handpiece and temperature was evaluated using a fiber optic thermometer. Osteotomies completed in cortical bone had an average duration that was significantly higher than in cortico-cancellous bone. The maximum temperature was higher in the cortical group than in the cortico-cancellous- 44.06 vs. 40.07° C, respectively. Although these differences were not found to be statistically significant, mean temperature and osteotomy duration resulted in temperatures significantly higher in the cortical group.[72] The resistance of this compact cortical bone against the drill results in frictional heat resulting in an increase in bone temperature that spreads along the cortical bone in all directions.[73]

Irrigation

The purpose of irrigation during osteotomy preparation is to aid in cooling of the implant drill and surrounding bone as the frictional heat of drilling causes an increase in temperature.[74] This was seen by Benington et al. when osteotomies were drilled in a bovine mandibular model with three different drills, using no irrigation to allow for accurate thermal imaging with infrared thermography, reporting temperatures as high as 130.1°C.[75] Augustin et al. evaluated the influence irrigation on drilling in combination with other variables such as drill diameter, drill speed, feed rate and drill point angle. Osteotomies were prepared using a drill press on cortical porcine femurs at 188, 462, 1,140 and 1,820 RPM, and temperatures were measured using a thermocouple placed 0.5 mm from the osteotomy site 3 mm in depth. All drills were used 40 times before being replaced by a new drill. Experimental groups received external irrigation at 26° C while the control groups did not. They found that for every combination of drill speed and drill diameter during drilling, the temperature was far below the critical temperature threshold of 47° C with the use of external irrigation. Without external irrigation, temperatures ranged from 31.4-55.5° C, exceeding the critical threshold.[76] This influence of irrigation on temperature decrease has been further substantiated by many additional studies.[77, 78]

Irrigation during preparation can be either external, internal, or a combination of both. Double irrigation externally and internally allows for better cooling and decreased temperatures of the cortical bone.[79] Depending on the depth of the osteotomy, internal or external irrigation may be sufficient to adequately cool the bur and the surrounding bone.[53] Strbach et al. studies showed that external irrigation adequately cools the bone at the surface, but in deeper preparations, irrigation may not adequately reach the more apical extension of the osteotomy. In such cases, a combined irrigation method would be preferred over external irrigation only.[80, 81]

Barrak et al. evaluated the difference between free-hand vs. guided osteotomy preparation at 800 RPM with irrigation fluid at different temperatures—20° C, 15° C, or 10° C. They found that cooled irrigation to 10° C was sufficient in both free-hand and guided osteotomy preparation at controlling the temperature of the bone, whereas room temperature irrigation resulted in greater temperature changes.[82]

Guided vs. Free-Hand Placement

With the advances in technology, there has been a shift towards guided surgery, with increased precision in implant placement. Although implant placed with surgical guides decreases the likelihood for less-than-ideal implant placement, the surgical limitations include access intraorally, longer drills, key systems, and decreased access for irrigation. Windows are prepared into the surgical guides to not only increase visualization for proper seating of the surgical guide but also to increase the ability for irrigate to reach the drills during osteotomy preparation. A decrease in irrigation, as described previously, can significantly increase temperatures of the bone during drilling.

Misir et al. evaluated whether there was an increase in temperatures with guided osteotomy preparation compared to non-guided classical implant site preparation in bovine femoral cortical bone samples. Thermocouples were vertically placed at 3, 6 and 9 mm adjacent to the osteotomy preparation and measured temperature changes during drilling in a thermostat-controlled water bath. Room temperature saline was used for irrigation. The mean maximum temperatures found with and without surgical guides were 37.9° C and 30.2° C respectively. The temperature increase as depth increased from 3 to 6 to 9 mm (31.5° C, 35.2° C and 35.4° C) and was statistically significant between 3 and 6 mm and between 3 and 9 mm. Classical drilling resulted in mean temperature values of 28.8° C, 30.7° C and 31.1° C at 3, 6 and 9 mm respectively, and was found to be statistically significant compared to guided drilling.[83] This study showed a significant difference in heat generation during guided osteotomy preparation as compared to non-guided osteotomy preparation.

In the study by dos Santos et al., they assessed bone heating, drill deformation, and drill roughness during implant osteotomies using guided surgery and classic drilling techniques when drills were used 0, 10, 20, 30 and 40 times in rabbit tibias. Bone temperature was measured using a thermocouple in a separate osteotomy 1 mm from the osteotomy during drilling, revealing that the guided surgery technique generated significantly higher bone temperatures compared to the classic drilling method. Additionally, drill deformation increased with repeated use in both techniques, with the guided surgery group showing significant deformation after fewer uses. Although drill roughness increased with reuse in both groups, no statistically significant differences were observed between the subgroups or techniques. The temperature increased with the number of times the drills were used; however, neither technique produced bone temperatures high enough to cause thermal necrosis.[84]

Similarly, Barrak et al. investigated heat generation during osteotomy preparations performed guided vs. free hand on bovine ribs. Osteotomies were prepared at 800, 1200, 1500 and 2000 RPM, and bone temperatures were measured every 30 drilling cycles to assess the cumulative effects of drilling parameters. The guided group resulted in significantly elevated temperatures over the critical threshold for bone necrosis. The most significant contributing factors were the metal guide sleeve, high RPM, the sterilization protocol, and the number of times the drills were used.[85] This group also completed a follow up study to their 2017 and 2018 studies[82, 85], where they compared free hand to guided preparation at 1500 and 2000 RPM at irrigation temperatures of 20° C, 15° C, or 10° C. This study found that at 1500 RPM and 2000 RPM, guided drilling with irrigation at 20° C yielded temperature values exceeding the critical temperature threshold at drill diameters of 3.0 and 3.5 mm. This was also seen with 3.5 mm freehand drilling at 2000 RPM. With 10° C irrigation, temperatures remained below the critical threshold in both free-hand and guided drilling.[86] This study shows that there is likely an influence of the temperature of the irrigation, access of the irrigation to cool the bone and drill with guided preparation, as well as the speed at which the osteotomy is being prepared.

RPM

Increased speed of rotation increases the amount of friction heat generated. In osteotomy preparation, there is a range of RPM's that may be used for drilling, which may be influenced by the recommendation of the drill system's recommended guidelines. A study by Reingewirtz et al. found an increase in temperatures up to 24,000 RPM, which remained constant up to 40,000 RPM.[58] Some studies have shown that when looking at RPM as a variable without the use of irrigation, an increase in speed also increases the temperature of the bone, but the addition of irrigation can negate the rise in temperature.[76] Soldatos et al. found a statistically significant three-way interaction between drill design, drill diameter, and RPM on temperature change (ΔT). Densah® burs showed an inverse relationship between diameter and ΔT across all speeds, while MIS® drills only followed this trend at 1000 RPM.[11] This emphasizes the importance of following manufacturer's recommendation for speed during osteotomy preparation.

Duration of Drilling

With increased amount of time drilling, there is a corresponding increase in heat generation due to a longer duration of friction being generated. This can be seen when drills are overused and are not cutting efficiently or in different methods of osteotomy preparation, such as preparations with a piezoelectric handpiece.[57, 66] Bhargava et al. compared temperature changes following osteotomy preparation with use of osteotomes, piezoelectric surgery, OD burs and conventional drilling. The drilling protocols were completed at 1100 RPM under external irrigation. The piezoelectric surgery group took the longest time to prepare the osteotomy and showed the highest change in temperature by approximately 5^0C, followed by OD by approximately 1^0C, and then osteotomes and conventional drills with no statistically significant difference between osteotomes and conventional drilling.[21]

Depth

Depth may play a role in increased temperature as the depth of the osteotomy increases with certain methods of preparation. Misic et al. found an increase in temperature at 5 mm with conventional drilling, which they attributed potentially to the design of the drill or the efficacy of the irrigation at reducing the friction heat at this depth. Additionally, deeper osteotomies are subjected to longer drilling times, exposing the bone to an increased time under friction, possibly resulting in increased temperature.[87] Misic et al. similarly found a statistically significant difference in temperature at greater depths compared to shallower depths during guided surgery.[83] This finding also may be attributed to the lack of irrigation in deeper sites rather than the variable depth itself.

Drill Design

There are multiple components of the drill that may influence the preparation of bone and ultimately the resulting heat generation. Some of those include material hardness and drill design.[88] Harder materials may better withstand the friction created while drilling, resisting damage along their cutting edges and ultimately retaining a higher cutting efficiency over multiple uses.[66] The design of the drill has multiple components including the minor cutting edge, major cutting edge, chisel edge, point angle, flutes, helix angle, relief angle, clearance angle, and rake angle.[89] Chacon et al evaluated the heat production of three drills with thermocouples 0.5 mm from the osteotomy, prepared under 2.4 kgf at 2,500 RPM with external irrigation in cortical bovine femurs. The drills were designed in three ways- a triple twist drill with a relief angle, a triple twist drill without a relief angle, and a double twist drill with a relief angle. They found that the drill without a relief angle resulted in temperatures above the critical threshold, compared to those with relief angles.[90] Without a relief angle, the chips created by the cutting edge are not cleared which results in an increase in friction and in turn, heat generation.

Scarano et al. compared drill designs of the triple twist cylinder to the quadruple twist conical drills in a bovine bone model. They found that triple twist cylinder drills generated more heat than quadruple twist conical drills, emphasizing the importance of having the right number of cutting edges enhancing cutting efficiency.[91] In the study by Soldatos et al., they assessed temperature changes during implant osteotomy preparations in fresh human cadaver tibiae, comparing straight drills with slightly tapered drills under various drilling speeds. Temperature measurements were taken using thermocouples placed inside the osteotomy sites, with external irrigation applied throughout the procedures. Drilling was conducted at speeds of 800, 1000, and 1200 RPM. The study found that tapered drills generated significantly higher temperatures than straight drills, although none exceeded the critical threshold of 47°C. Additionally, as drill diameter increased, the temperature rise decreased, particularly notable with the tapered burs.[13] These findings highlight the influence of drill design and diameter on thermal changes during implant site preparation.

Drill Wear

Overuse of surgical drills may result in wear of the cutting edges, in turn decreasing the cutting efficiency. A decrease in efficiency will result in increased frictional heat generation. Allan et al. evaluated this concept by comparing a new drill to one that has been partly worn after 600 uses and to one that was used for many months and measured the temperature of the bone as a result of its use in pig mandibles. A K-type thermocouple evaluated the temperature inside the osteotomy after the osteotomy was prepared to 5 mm depth with 12kgf at 20,000 RPM. The new drill produced the smallest change in temperature, with a mean change of 7.5° C, compared to the drill that was used 600 times, with a mean change of 13.4° C, and the drill that was used for several months, with a mean change of 25.4° C.[92] This study however did not use irrigation during preparation, which does not represent clinical practice during implant site preparation.

Ercoli et al. study more closely represented osteotomy preparation in clinical practice. 100 Osteotomies were prepared using a drill press via intermittent cutting motion with 2kgf at 1,500 RPM on bovine ribs with external irrigation. Osteotomies were completed with variant drills, and the temperature was evaluated with a thermocouple at 5mm and 15mm depth, 1 mm from the drilling site. The drills were discarded or considered a failure if they were fractured or visibly damaged, showed an inability to complete the first drilling step of 2 mm within 5 minutes, or caused a temperature increase greater than 47° C for 3 consecutive osteotomies. There was a significant decrease in removal rate after 10 osteotomies for both the 2 mm and 3 mm diameter drills, but the 2 mm drill showed more variability than the 3 mm. There was no statistically significant difference in temperature at 5 mm vs 15 mm in depth with either of the drills. In 5 of the osteotomies prepared, the temperature recorded at the 15 mm location exceeded 47° C and coincided with a decrease in the rate of drill advancement, likely as a result of decreased cutting efficiency and increased time in drilling. The effects of drill use, however, did not reach statistical significance in relation to temperature.[66] Möhlhenrich et al.'s 2015 systematic review failed to find a significant amount of literature to support whether drill wear definitely increases temperatures of the surrounding bone.[50] Similarly studies by Misir et al., Jochum et al., Oliveira et al., and Allsobrook *at al.* described non-significant elevation in temperature when drills were used 50, 40, 50 and 40 times respectively.[59, 83, 93, 94]

Drill Diameter

In looking at whether an increase in drill diameter results in an increase in temperature, Eriksson and Adell completed a study where implants were placed in the human mandibles following the osseointegration technique described by Branemark.[95, 96] While increasing the drill diameter from 2 mm to 3 mm at 1,500 to 2,000 RPM under irrigation and intermittent and low pressure, the temperature of the bone was recorded using a thermocouple of 0.5 mm from the osteotomy preparation. They found that the temperature changes varied from -2.4° C to + 4.1° C from an initial average temperature of 29.2° C. The maximum mean temperature reached 30.3° C, but this never exceeded more than 5 seconds in duration, never reaching the critical temperature threshold.[54] In contrast, Augustin et al.'s previously described study found that when external irrigation was not used, drill diameters of 4.5 mm compared to those of 2.5 and 3.2, resulted in temperature values above the critical level. When external irrigation was used, however, no values were above the threshold.[76] This shows that although increasing drill diameter may have an influence on temperature during drilling, it may be counteracted when irrigation is used. Conversely, Strbac et al, found that temperature was inversely proportional to the diameter of the drill, and the highest increase in temperature was created with the 2 mm spike drill.[80, 81] This was also found in Soldatos et al.'s study in which the highest recorded temperature was found with the initial drills, and that the temperature decreased as drill diameter increased.[12] This may be attributed to the increased time in which the spike drill requires to get through the thickness of the cortical plate.

Clogged Drill Flutes

For the bone chips, created through the cutting motion of the bur; to be removed from the osteotomy as the drill twists, the chips must follow from the major cutting edge following the spiral path up along the flutes to the surface. The flutes have a greater tendency to clog when the depth of the hole becomes more appreciable compared to the diameter, resulting in increased torque.[89] Although the study by Wiggins and Malkin did not directly look at temperature, it can be assumed based on the other mentioned studies that an increase in torque due to friction would likely increase temperature production. This is substantiated by Chacon et al.'s study where drills without relief angles resulted in temperatures above the critical threshold.[90]

Conclusions

The relationship between implant osteotomy preparations and the heat generated is multifactorial and is likely not due to one single variable. Reducing surgical trauma is one-way providers can attempt to limit the less-than-ideal post-operative complications. Continued research focusing on reducing the amount of surgical trauma during implant osteotomy preparation and implant placement is paramount to the long-term success of implants, especially as different techniques are established and materials and instruments are implemented in clinical practice.

TABLES

Table 1: Temperature Evaluation Studies

Article	Study Model	Study Design	Variable of Evaluation	Findings
Eriksson and Albrektsson 1983[7]	Hare and Rabbit Tibia	Hollow thermal chamber heated 10 weeks after placement. Temperature evaluated with thermocouple	Heat effects on bone 50° C for 1 minute (A), 47° C for 5 minutes (B) and 47° C for 1 minute (C)	Critical Threshold 47° C for 1 minute. Hyperemia and blood flow stasis at 50° C. Fat tissue resorption peaking at 2 weeks, followed by fat cell invasion of 150% to 200% increase in the groups A and B. Bone remodeling 20 to 30 days following thermal injury in groups A and B, resulting in 30% to 40% less bone compared to initial
Eriksson and Albrektsson 1984[34]	Rabbit, Dog, Human Femur	Thermocouple placed 0.5 mm from osteotomy and measured after drilling at 20,000 RPM with irrigation	Heat produced during drilling	Rabbit- mean temperature 40° C for an average increase of 8° C Dog- peak temperature 65° C Human- peak temperature 96° C
Eriksson and Albrektsson 1984[8]	Rabbit Tibia	Titanium implant inserted into bone with hollow chamber. Implant heated with voltage-regulated heating element and thermocouple placed 0.5 mm from the implant. Implants healed	Heat effects on bone growth and integration 50° C for 1 minute (A), 47° C for 1 minute (B) and 44° C for 1 minute (C) Contralateral tibia control with no heat	(Control) Osseointegrated implants with hard tissue growth in hollow chamber (A) lack of osseointegration, no hard tissue in hollow chamber, and lack of blood vessels (B) Implants able to be screwed out of bone and larger amount of hard tissue

		for 4 weeks and then removed with trephine.		in chamber, histologically similar bone to control (C) Implants osseointegrated with bone hollow chamber, histologically similar bone to control
Eriksson and Adell 1986[54]	Human Mandible	Temperature evaluation with thermocouple 0.5 mm from osteotomy while expanding osteotomy drilling at 1,500 to 2,000 RPM with irrigation	Increasing diameter from 2 mm to 3 mm	Temperature varied from -2.4° C to + 4.1° C from initial average temperature of 29.2° C. Maximum mean temperature of 30.3° C. Maximum temperatures never exceeded 5 seconds and did not reach critical threshold
Trisi et al. 2015[65]	Sheep Iliac Crest	Osteotomies heated to either 50°C for 1 minute or 60°C for 1 minute compared to a control, with implants placed and evaluated 2 months after healing	Bone to implant contact %, infrabony pocketing and crestal bone loss	Sites heated to 50°C for 1 minute showed no statistically significant difference in bone to implant contact percentage compared to the control. Significant differences in bone to implant contact percentage were found between 60°C for 1 minute when compared to the control. These implants were also associated with significant differences in infrabony pocket depth in the group heated to 60°C as well as crestal bone resorption compared to the control.
Bhargava et al. 2023[21]	Porcine Ribs	Temperature evaluation with a thermocouple 1 mm from the osteotomy site and insulated with sticky wax at the canal opening. OD burs were used at 1100 RPM with irrigation. Conventional drilling burs were used at 1100 RPM with irrigation. Piezoelectric surgery groups were used under irrigation	Temperature changes between osteotomes, conventional drilling, OD and piezoelectric surgery and the corresponding insertion torque values for each group	Piezoelectric surgery group showed highest change in temperature, followed by OD and then osteotomes and conventional drills with no statistically significant difference between osteotomes and conventional drilling. Implants inserted with the osseodenficiation protocol exhibited the higest insertion torque values, followed by the piezo, conventional drills, and then osteotomes with no statistically significant difference between conventional drills and osteotomes.

Di Fiore et al. 2018[67]	Bovine Ribs	Temperature evaluated by a thermal probe comparing intermittent vs. continuous cutting using room temperature saline and refrigerated saline at 1200 RPM	Intermittent vs continuous cutting and room temperature vs refrigerated irrigation	No difference in temperature between intermittent and continuous cutting. Refrigerated saline had lower overall temperatures than room temperature saline
Gehrke et al. 2013[55]	Bovine Ribs	Temperature was evaluated with a K-type thermopair 0.5 mm from the osteotomies	Intermittent vs continuous movement and external irrigation vs double irrigation	Double irrigation produced a smaller temperature increase compared to external irrigation (1.11° C vs 3.68° C). There was a significant difference in temperature increase between intermittent vs continuous movement (1.72° C vs 3.07° C)
Gehrke et al. 2014[79]	Synthetic Bone Blocks	Temperature evaluated with an experimental computed machine of trephine drills without irrigation, with external irrigation or with double irrigation	Irrigation	Double irrigation resulted in smaller increase in temperature compared to external irrigation alone
Benington et al. 2002[53]	Bovine Mandible	Temperature evaluated using infrared thermography on osteotomies drilled with a 2 mm twist drill and trephine under 1.7 kgf at 2,500 RPM with normal saline irrigation either internally or externally	Irrigation	No statistical difference between internal vs external irrigation methods in temperature changes
Stelzle et al 2014[69]	Porcine Head	Temperature evaluated using a thermocouple on implant site preparation with conventional drills and piezosurgery	Pressure	Piezosurgery had an increase in temperature with increased load

		preparation at increasing load intervals		
Raj et al. 2021[70]	Bovine Femur	Temperatures evaluated using infrared thermography on osteotomies prepared at 1500, 2000, and 2500 RPM, at 1.2 and 2.4 kgf pressure, and with room temperature saline vs. chilled saline	Pressure, RPM, and irrigation temperature	The highest temperature was observed at 2000 RPM, 1.2 kgf pressure and room temperature irrigation. The lowest temperature generated was using 2500 RPM, 2.4 kgf hand pressure and chilled irrigation. None of the experimented parameters generated heat above the critical threshold for bone necrosis
Matthews et al. 1972[56]	Human Femur	Temperatures evaluated using a thermocouple 0.5, 1 and 2.0 mm from the osteotomy under irrigation at 348, 885 and 2900 RPM at 2, 6, 12 kgf. One drill was used over 200 times to evaluate drill wear.	Pressure, RPM, irrigation, and drill wear	Temperatures greater than 100 ° C were recorded in 37/158 examinations without irrigation. Irrigation was highly effective in limiting the maximum temperature elevations. There was a decrease in temperature with an increase in force and increase in RPM. The worn drill caused greater maximum temperature elevations and longer durations of temperature elevation.
Lajolo et al. 2018[71]	Porcine Rib	Temperatures evaluated using infrared thermography of osteotomy preparation with conventional drills and piezoelectric device at 1 kgf and 1.5 kgf under irrigation	Pressure and mode of preparation	Temperature increases exceeding the threshold value of 10° C occurred in half of the samples prepared with the piezoelectric device and was 2 times more likely to increase the osteotomy past the critical threshold. No statistically significant differences found based on pressure load applied
Rashad et al. 2012[57]	Bovine Rib	Temperatures evaluated using thermocouples 1.5 mm from site prepared by conventional drills and piezoelectric at 5, 8, 10, 15 and 20 N	Pressure, mode of preparation, and irrigation amount	No statistical difference between pressures. Increased time and heat associated with piezoelectric preparation. A higher irrigation amount decreased temperature for the piezoelectric but not for conventional drilling

Reingewirtz et al. 1997[58]	Ox Femur	Temperatures evaluated using a thermocouple 0.8 mm from drilling instrument using 3 different motors, drilling from 400 and 40,000 RPM	Pressure, drilling time, RPM, and type of motor	Temperature elevation was similar for all 3 motors tested. Increasing pressure did not exert an increase in temperature but decreased drilling time. Temperature rise reached a maximum at 24,000 RPM and stayed relatively constant up to 40,000 RPM
Lamazza et al. 2016[72]	Bovine Rib and Femur	Temperatures evaluated in osteotomies prepared with a piezoelectric handpiece and temperatures evaluated using a fiber optic thermometer	Cortical vs. Corticocancellouos bone and duration of drilling	Mean temperature and osteotomy duration resulted in temperatures significantly higher in the cortical group
Benington et al. 1996[53]	Bovine Mandible	Temperatures evaluated using infrared thermography under no irrigation using a round bur, a 2 mm twist drill and 2 mm pilot drill	Temperature changes and based on drill size	The maximum recorded temperatures were 82.7°C for the round bur, 130.1°C for the twist drill, and 126.3°C for the pilot drill.
Augustin et al 2008	Porcine Femur	Temperatures evaluated in osteotomies prepared with and without irrigation with a thermocouple 0.5 mm from osteotomy	Irrigation, drill diameter, speed, point angles and feed-rates	For every combination of drill speed and drill diameter during drilling, the temperature was far below the critical temperature threshold of 47° C with the use of external irrigation. Without external irrigation, temperatures ranged from 31.4-55.5° C, exceeding the critical threshold. When irrigation is not used, an increase in drill diameter and drill speed raises the temperature. No statistical significance of drill point angle on temperature. Lower feed rates were statically significant in increasing temperature
Misir et al. 2009[83]	Bovine Femur	Temperature evaluation with a thermocouple of 3, 6 and 9 mm in	Guided vs non-guided osteotomy preparation. Depth	Mean maximum temperatures found with and without surgical guides were 37.9° C and 30.2° C

		depth. Osteotomy preparation with 2.0 kgf and 1,500 RPM with room temperature irrigation	of drills at 3, 6, and 9 mm	respectively. The temperature increase as depth increased from 3 to 6 to 9 mm (31.5° C, 35.2° C and 35.4° C) and was statistically significant between 3 and 6 mm and between 3 and 9 mm. Non-guided drilling resulted in mean temperature values of 28.8° C, 30.7° C and 31.1° C at 3, 6 and 9 mm respectively, and was found to be statistically significant compared to guided drilling. No statistically significant change in temperature was found when drills were used up to 50 uses.
dos Santos et al. 2014	Rabbit Tibias	Temperature evaluation with a thermocouple in an osteotomy 1 mm from osteotomy comparing guided vs. free hand at 1200 RPM with external irrigation using burs 0, 10, 20, 30 and 40 times	Guided vs. Freehand temperature changes, number of uses, drill deformation and surface roughness	Guided surgery technique generated significantly higher bone temperatures compared to the classic drilling method. Drill deformation increased with repeated use in both techniques, with the guided surgery group showing significant deformation after fewer uses. No statistically significant differences were observed between the subgroups or techniques in surface roughness. The temperature increased with the number of times the drills were used; however, neither technique produced bone temperatures high enough to cause thermal necrosis.
Barrak et al. 2017[82]	Bovine Ribs	Temperature evaluation with a thermocouple of free hand vs. guided osteotomy preparation at 800 RPM with irrigation fluid at 20° C, 15° C, or 10° C.	Temperature of irrigant in free-hand and guided osteotomy preparation	Cooled irrigation at 10° C was sufficient in both free-hand and guided osteotomy preparation at controlling the temperature of the bone at low RPM, whereas room temperature irrigation resulted in greater temperature changes.
Barrak et al. 2018[85]	Bovine Ribs	Temperature evaluation with a thermocouple 1	Temperature of osteotomy at different drill	The guided group resulted in significantly elevated temperatures over the critical

		mm away from the final osteotomy using free hand vs guided sleeves with irrigation at 800, 1200, 1500 and 2000 RPM	speeds and drill wear in guided vs free hand preparation	threshold for bone necrosis. The most significant contributing factors were the metal guide sleeve, high RPM, the sterilization protocol and the number of times the drills were used
Barrak et al. 2019[86]	Bovine Ribs	Temperature evaluation with a thermocouple of free hand vs. guided osteotomy preparation at 1500 and 2000 RPM with irrigation fluid at 20° C, 15° C, or 10° C.	Temperature of irrigant in free-hand and guided osteotomy preparation, and RPM influence	1500 RPM and 2000 RPM, guided drilling with irrigation at 20° C yielded temperature values exceeding the critical temperature threshold at drill diameters of 3.0 and 3.5 mm, which was also seen at 3.5 mm freehand drilling at 2000 RPM. 10° C irrigation temperatures remained below the critical threshold in both free-hand and guided drilling.
Sindel et al. 2017[78]	Sheep Mandible	Temperature evaluation with thermocouple 3 mm from osteotomies prepared with 2.8, 3.4, 3.8 and 4.4 mm diameter burs with 12 ml/min and 30 ml/min irrigation and without irrigation	Irrigation with drill diameter	No irrigation group was statistically higher in all 4 diameter burs than irrigation group. Diameters 2.8, 3.4 and 3.8 were significantly higher than the 4.4 mm bur with irrigation.
Strbac et al. 2014[80]	Bovine Rib	Temperature evaluation using thermoprobes 1 and 2 mm from the osteotomy at various depths. Osteotomies prepared with 2, 3.5, 4.3 and 5 mm drills without irrigation, with external, internal and combined irrigation	Irrigation and depth	Highest temperature increase without irrigation, followed by external, combined irrigation, and then internal irrigation. Higher temperatures were noted near the crest especially in deeper osteotomies
Strbac et al. 2014[81]	Artificially Manufactured Bovine Specimen	Temperature evaluation using thermoprobes 1 and 2 mm from the osteotomy at various depths.	Irrigation, depth and diameter	External irrigation showed higher temperatures than internal and combined irrigation at both 10 and 16 mm. Higher temperatures were noted with the 2 mm

		Osteotomies prepared with 2, 3.5, 4.3 and 5 mm drills to 10 mm and 16 mm depth without irrigation, with external, internal and combined irrigation		twist drill compared to the 3.5, 4.3 and 5 mm drills.
Soldatos et al. 2016[12]	Polyurethane foam blocks	Temperature evaluation using thermocouples inside the osteotomy, with preparations at 800, 1000 and 1200 RPM with and without external irrigation	Drill design and diameter and use of irrigation	The highest temperature increase occurred with D1 initial drills (65.0 ± 6.9°C), while the lowest was with D2 initial drills (47.3 ± 2.9°C). AS drill diameter increased, maximum temperature decreased. The use of irrigation significantly reduced the temperature elevations across drill types and speeds
Soldatos et al. 2022[13]	Fresh Human Cadaver Tibiae	Temperature evaluation using thermocouples inside the osteotomy, with preparations at 800, 1000 and 1200 RPM with external irrigation using straight and tapered drills	Drill design, drill diameter	Tapered drills generated significantly higher temperatures than straight drills, although none exceeded the critical threshold of 47 °C. As drill diameter increased, the temperature rise decreased, particularly notable with the tapered drills
Soldatos et al 2022.[97]	Fresh Human Cadaver Tibiae	Temperature evaluation using thermocouples inside the osteotomy, with preparations at 800, 1000 and 1200 RPM with external irrigation using straight MIS® and tapered Densah® burs	Drill design, diameter, RPM, and drill use	A statistically significant three-way interaction between drill design, drill diameter, and RPM on temperature change (ΔT). Densah® burs an inverse relationship between diameter and ΔT across all speeds, while MIS® drills only followed this trend at 1000 RPM. No temperature increases exceeded the critical 47 °C threshold, and using drills up to 20× did not significantly affect ΔT
Chacon et al. 2006[90]	Bovine Femur	Temperature evaluation of drills with and without relief angles	Drill Design	The drill without a relief angle, resulted in temperatures above the

		during osteotomy preparation at 2,500 RPM under irrigation		critical threshold, compared to those with relief angles
Scarano et al 2009[91]	Bovine Femur	Temperature evaluation using infrared thermography during osteotomy preparation using triple twist cylindrical drills compared to quadruple twist conical drills	Drill Design	The cylindrical drills (triple twist) generated significantly higher temperatures than the conical drills (quadruple twist), with cortical bone temperatures averaging 31.2 ± 0.5°C for cylindrical drills and 29.1 ± 0.6°C for conical drills
Jochum et al. 2000[59]	Pig Mandibles	Temperature evaluation and wear on drills during repeated use under external irrigation using a thermocouple 0.5 mm from drilling site	Drill Wear	All recorded temperatures remained below the critical threshold; however, drills used more than 40 times exhibited a statistically significant increase in temperature readings.
Oliveira et al. 2012[93]	Bovine Ribs	Temperature evaluation using thermocouple 1 mm from osteotomy site during repeated use at 800 RPM under external irrigation	Drill Wear using stainless steel drills vs zirconia-based ceramic drills	Stainless steel drills generated significantly higher bone temperatures (1.6°C) compared to ceramic drills 1.3°C). No significant association was found between drilling force and temperature increase. Scanning electron microscopy revealed no severe signs of wear on either drill type after 50 uses
Allsobrook et al. 2011[94]	Bovine Ribs	Temperature evaluation using thermocouple 1 mm from osteotomy sites for 50 osteotomies at 1200 RPM under external irrigation	Drill Wear	Bone temperatures did not exceed 27.7°C after 50 uses
Allan et al. 2005[92]	Pig Mandible	Temperature evaluation with thermocouple inside the osteotomy prepared at 20,000 RPM with	Drill Wear	The new drill produced the smallest change in temperature, with a mean change of 7.5° C, compared to the drill that was used 600 times, with a mean change of 13.4° C, and the drill that was

		a new drill, a drill used 600 times, and drill used for several months without irrigation		used for several months, with a mean change of 25.4° C.
Ercoli et al. 2004[66]	Bovine Ribs	Temperature evaluation at 5 mm and 15 mm with a thermocouple 1 mm from osteotomy after drill usage up to 100 times with irrigation	Drill Wear	There was no statistically significant difference in temperature at 5 mm vs 15 mm in depth with either of the drills. In 5 of the osteotomies prepared, the temperature recorded at the 15 mm location exceeded 47° C, and coincided with a decrease in the rate of drill advancement.
Misic et al. 2011[87]	Porcine Rib	Temperature evaluation using a thermocouple comparing bone condensing to conventional drilling	Depth, bone condensing vs. drilling	Temperatures consistently decreased through bone condensing method where as they spiked at 5 mm depth when drilling and then decreased

Table 2: Cortical Thickness References

Article	Study Model	Location	Cortical Thickness
Eriksson and Albrektsson 1984[34]	Rabbit, Dog, Human	Femur	1.5 mm, 3.5 mm, 6.5 mm respectively
Katranji et al. 2007[36]	Human Cadaver	Maxilla and mandible	Buccal cortical thicknesses were 1.69 mm (molar), 1.43 mm (premolar) and 1.04 mm (anterior) in the edentulous maxilla; 2.06 mm (molar), 1.78 mm (premolar) and 1.36 mm (anterior) in the edentulous mandible; 2.23 mm (molar), 1.62 mm (premolar) and 1.59 mm (anterior) in the dentate maxilla; and 1.98 mm (molar), 1.20 mm (premolar) and 0.99 (anterior) in the dentate mandible1.69 mm (molar), 1.43 mm (premolar) and 1.04 mm (anterior) in the edentulous maxilla; 2.06 mm (molar), 1.78 mm (premolar) and 1.36 mm (anterior) in the edentulous mandible; 2.23 mm

			(molar), 1.62 mm (premolar) and 1.59 mm (anterior) in the dentate maxilla; and 1.98 mm (molar), 1.20 mm (premolar) and 0.99 (anterior) in the dentate mandible
Ono et al. 2008[35]	Human CBCT	Buccal of posterior maxilla and mandible	1.09 to 2.12 mm in the maxilla and 1.59 to 3.03 mm in the mandible
Ko et al. 2017[37]	Human CBCT	Maxilla and Mandible crest	Crestal cortical bone thickness was greatest in the posterior mandible (1.07 ± 0.47 mm) followed by the anterior mandible (0.99 ± 0.36 mm), anterior maxilla (0.82 ± 0.30 mm) and finally the posterior maxilla (0.75 ± 0.35 mm)
Miyamoto et al. 2005[38]	Human	Mandible	2.22 ± 0.47 mm
Bhargava et al. 2023[21]	Porcine	Rib	2.5- 2 mm
Gerlach et al. 2013[39]	Human CBCT	Mandible	2.00 ± 0.15 mm
Maeda et al. 2020[40]	Human CT	Tibia	6.2 to 11.3 mm in young men, 4.2 to 9.3 mm in young women, 5.3 to 8.9 mm in elderly men, and 4.8 to 7.6 mm in elderly women
Lajolo et al 2017[71]	Porcine	Rib	2 mm
Matthews et al 1972[56]	Human Cadaver	Femur	5 mm
Augustin et al. 2009[98]	Porcine	Femur	4-5 mm
Misic et al. 2011	Porcine	Rib	2 mm

Table 3: Factors Affecting Heat Generation of Bone

Operator Related Factors	**Drill Related Factors**	**Patient Related Factors**
RPM Applied Pressure Irrigation Duration of Drilling Depth Technique Guided vs. Free hand	Drill design Flutes Drill Wear Drill Diameter Drill Material Clogged Drill Flutes	Bone Density Cortical Thickness Osteotomy Diameter Systemic Conditions

References

(1) Abraham, C. M. A brief historical perspective on dental implants, their surface coatings and treatments. *Open Dent J* **2014**, *8*, 50-55. DOI: 10.2174/1874210601408010050.

(2) Brånemark, P. I. Osseointegration and its experimental background. *J Prosthet Dent* **1983**, *50* (3), 399-410. DOI: 10.1016/s0022-3913(83)80101-2.

(3) Albrektsson, T.; Brånemark, P.-I.; Hansson, H.-A.; Lindström, J. Osseointegrated titanium implants: requirements for ensuring a long-lasting, direct bone-to-implant anchorage in man. *Acta Orthopaedica Scandinavica* **1981**, *52* (2), 155-170.

(4) Manor, Y.; Oubaid, S.; Mardinger, O.; Chaushu, G.; Nissan, J. Characteristics of early versus late implant failure: a retrospective study. *J Oral Maxillofac Surg* **2009**, *67* (12), 2649-2652. DOI: 10.1016/j.joms.2009.07.050.

(5) Paquette, D. W.; Brodala, N.; Williams, R. C. Risk factors for endosseous dental implant failure. *Dent Clin North Am* **2006**, *50* (3), 361-374, vi. DOI: 10.1016/j.cden.2006.05.002.

(6) Mishra, S. K.; Chowdhary, R. Heat generated by dental implant drills during osteotomy-a review: heat generated by dental implant drills. *J Indian Prosthodont Soc* **2014**, *14* (2), 131-143. DOI: 10.1007/s13191-014-0350-6.

(7) Eriksson, A. R.; Albrektsson, T. Temperature threshold levels for heat-induced bone tissue injury: a vital-microscopic study in the rabbit. *J Prosthet Dent* **1983**, *50* (1), 101-107. DOI: 10.1016/0022-3913(83)90174-9 From NLM Medline.

(8) Eriksson, R.; Albrektsson, T. The effect of heat on bone regeneration: an experimental study in the rabbit using the bone growth chamber. *Journal of Oral and Maxillofacial surgery* **1984**, *42* (11), 705-711.

(9) Oh, T. J.; Yoon, J.; Misch, C. E.; Wang, H. L. The causes of early implant bone loss: myth or science? *Journal of periodontology* **2002**, *73* (3), 322-333.

(10) Huwais, S.; Meyer, E. G. A Novel Osseous Densification Approach in Implant Osteotomy Preparation to Increase Biomechanical Primary Stability, Bone Mineral Density, and Bone-to-Implant Contact. *International Journal of Oral & Maxillofacial Implants* **2017**, *32* (1).

(11) Soldatos, N.; Pham, H.; Fakhouri, W. D.; Ngo, B.; Lampropoulos, P.; Tran, T.; Weltman, R. Temperature Changes during Implant Osteotomy Preparations in Human Cadaver Tibiae Comparing MIS® Straight Drills with Densah® Burs. *Genes* **2022**, *13* (10), 1716.

(12) Soldatos, N.; Gozalo, D.; Font, K.; Moreno, D.; Powell, C. Temperature changes during implant osteotomies utilizing three different implant systems: A pilot study. *JIACD* **2016**, *8* (7), 34-43.

(13) Soldatos, N.; Nelson-Rabe, L.; Palanker, N.; Angelov, N.; Romanos, G.; Weltman, R. Temperature Changes during Implant Osteotomy Preparations in Fresh Human Cadaver Tibiae, Comparing Straight with Tapered Drills. *Materials* **2022**, *15* (7), 2369.

(14) Albrektsson, T.; Albrektsson, B. Microcirculation in grafted bone: A chamber technique for vital microscopy of rabbit bone transplants. *Acta Orthopaedica Scandinavica* **1978**, *49* (1), 1-7.

(15) Turkyilmaz, I.; Aksoy, U.; McGlumphy, E. A. Two alternative surgical techniques for enhancing primary implant stability in the posterior maxilla: a clinical study including bone density, insertion torque, and resonance frequency analysis data. *Clinical implant dentistry and related research* **2008**, *10* (4), 231-237.

(16) Trisi, P.; De Benedittis, S.; Perfetti, G.; Berardi, D. Primary stability, insertion torque and bone density of cylindric implant ad modum Branemark: is there a relationship? An in vitro study. *Clinical oral implants research* **2011**, *22* (5), 567-570.

(17) Ottoni, J. M. P.; Oliveira, Z. F. L.; Mansini, R.; Cabral, A. M. Correlation between placement torque and survival of single-tooth implants. *International Journal of Oral & Maxillofacial Implants* **2005**, *20* (5).

(18) Yoon, H.-G.; Heo, S.-J.; Koak, J.-Y.; Kim, S.-K.; Lee, S.-Y. Effect of bone quality and implant surgical technique on implant stability quotient (ISQ) value. *The journal of advanced prosthodontics* **2011**, *3* (1), 10.

(19) Mohamed, S. H.; Seenivasan, M. K. Comparison of Osteoblastic Activity Around Endosseous Implants Placed with Osseodensification and Adaptive Osteotomy Techniques--A Split-Mouth Prospective Case-Control Study. *International Journal of Oral & Maxillofacial Implants* **2023**, *38* (1).

(20) Yeh, Y.-T.; Chu, T.-M. G.; Blanchard, S. B.; Hamada, Y. Effects on Ridge Dimensions, Bone Density, and Implant Primary Stability with Osseodensification Approach in Implant Osteotomy Preparation. *International Journal of Oral & Maxillofacial Implants* **2021**, *36* (3).

(21) Bhargava, N.; Perrotti, V.; Caponio, V. C. A.; Matsubara, V. H.; Patalwala, D.; Quaranta, A. Comparison of heat production and bone architecture changes in the implant site preparation with compressive osteotomes, osseodensification technique, piezoelectric devices, and standard drills: an ex vivo study on porcine ribs. *Odontology* **2023**, *111* (1), 142-153.

(22) Summers, R. B. A new concept in maxillary implant surgery: the osteotome technique. *Compendium (Newtown, Pa.)* **1994**, *15* (2), 152, 154-156, 158 passim; quiz 162.

(23) Shayesteh, Y. S.; Khojasteh, A.; Siadat, H.; Monzavi, A.; Bassir, S. H.; Hossaini, M.; Alikhasi, M. A comparative study of crestal bone loss and implant stability between osteotome and conventional implant insertion techniques: a randomized controlled clinical trial study. *Clinical implant dentistry and related research* **2013**, *15* (3), 350-357.

(24) Tsolaki, I. N.; Tonsekar, P. P.; Najafi, B.; Drew, H. J.; Sullivan, A. J.; Petrov, S. D. Comparison of osteotome and conventional drilling techniques for primary implant stability: An in vitro study. *Journal of Oral Implantology* **2016**, *42* (4), 321-325.

(25) Saker, M.; Ogle, O. Benign paroxysmal positional vertigo subsequent to sinus lift via closed technique. *Journal of oral and maxillofacial surgery* **2005**, *63* (9), 1385-1387.

(26) Anitua, E.; Alkhraisat, M. H.; Piñas, L.; Orive, G. Efficacy of biologically guided implant site preparation to obtain adequate primary implant stability. *Annals of Anatomy-Anatomischer Anzeiger* **2015**, *199*, 9-15.

(27) Lahens, B.; Neiva, R.; Tovar, N.; Alifarag, A. M.; Jimbo, R.; Bonfante, E. A.; Bowers, M. M.; Cuppini, M.; Freitas, H.; Witek, L. Biomechanical and histologic basis of osseodensification drilling for endosteal implant placement in low density bone. An experimental study in sheep. *journal of the mechanical behavior of biomedical materials* **2016**, *63*, 56-65.

(28) Romeo, D.; Chochlidakis, K.; Barmak, A. B.; Agliardi, E.; Lo Russo, L.; Ercoli, C. Insertion and removal torque of dental implants placed using different drilling protocols: An experimental study on artificial bone substitutes. *Journal of Prosthodontics* **2023**, *32* (7), 633-638.

(29) Capparé, P.; Vinci, R.; Di Stefano, D. A.; Traini, T.; Pantaleo, G.; Gherlone, E. F.; Gastaldi, G. Correlation between initial BIC and the insertion torque/depth integral recorded with an instantaneous torque-measuring implant motor: an in vivo study. *Clinical implant dentistry and related research* **2015**, *17*, e613-e620.

(30) Shalabi, M. M.; Wolke, J. G.; De Ruijter, A. J.; Jansen, J. A. Histological evaluation of oral implants inserted with different surgical techniques into the trabecular bone of goats. *Clinical oral implants research* **2007**, *18* (4), 489-495.

(31) Shalabi, M. M.; Wolke, J. G.; De Ruijter, A. J.; Jansen, J. A. A mechanical evaluation of implants placed with different surgical techniques into the trabecular bone of goats. *Journal of Oral Implantology* **2007**, *33* (2), 51-58.

(32) Koutouzis, T.; Huwais, S.; Hasan, F.; Trahan, W.; Waldrop, T.; Neiva, R. Alveolar ridge expansion by osseodensification-mediated plastic deformation and compaction autografting: a multicenter retrospective study. *Implant dentistry* **2019**, *28* (4), 349-355.

(33) Kold, S.; Bechtold, J.; Ding, M.; Chareancholvanich, K.; Rahbek, O.; Søballe, K. Compacted cancellous bone has a spring-back effect. *Acta Orthopaedica Scandinavica* **2003**, *74* (5), 591-595.

(34) Eriksson, A. R.; Albrektsson, T.; Albrektsson, B. Heat caused by drilling cortical bone: temperature measured in vivo in patients and animals. *Acta Orthopaedica Scandinavica* **1984**, *55* (6), 629-631.

(35) Ono, A.; Motoyoshi, M.; Shimizu, N. Cortical bone thickness in the buccal posterior region for orthodontic mini-implants. *International journal of oral and maxillofacial surgery* **2008**, *37* (4), 334-340.

(36) Katranji, A.; Misch, K.; Wang, H. L. Cortical bone thickness in dentate and edentulous human cadavers. *Journal of periodontology* **2007**, *78* (5), 874-878.

(37) Ko, Y. C.; Huang, H. L.; Shen, Y. W.; Cai, J. Y.; Fuh, L. J.; Hsu, J. T. Variations in crestal cortical bone thickness at dental implant sites in different regions of the jawbone. *Clinical implant dentistry and related research* **2017**, *19* (3), 440-446.

(38) Miyamoto, I.; Tsuboi, Y.; Wada, E.; Suwa, H.; Iizuka, T. Influence of cortical bone thickness and implant length on implant stability at the time of surgery—clinical, prospective, biomechanical, and imaging study. *Bone* **2005**, *37* (6), 776-780.

(39) Gerlach, N. L.; Meijer, G. J.; Borstlap, W. A.; Bronkhorst, E. M.; Bergé, S. J.; Maal, T. J. J. Accuracy of bone surface size and cortical layer thickness measurements using cone beam computerized tomography. *Clinical Oral Implants Research* **2013**, *24* (7), 793-797.

(40) Maeda, K.; Mochizuki, T.; Kobayashi, K.; Tanifuji, O.; Someya, K.; Hokari, S.; Katsumi, R.; Morise, Y.; Koga, H.; Sakamoto, M.; et al. Cortical thickness of the tibial diaphysis reveals age- and sex-related characteristics between non-obese healthy young and elderly subjects depending on the tibial regions. *Journal of Experimental Orthopaedics* **2020**, *7* (1), 78. DOI: 10.1186/s40634-020-00297-9.

(41) Goldstein, S. A.; Wilson, D. L.; Sonstegard, D. A.; Matthews, L. S. The mechanical properties of human tibial trabecular bone as a function of metaphyseal location. *Journal of biomechanics* **1983**, *16* (12), 965-969.

(42) LARSEN, C. G. N. J. COMPRESSIVE STRENGTH OF TIBIAL CANCELLOUS BONE. *Acta orthop. scand* **1983**, *54*, 819-825.

(43) Misch, C. E.; Qu, Z.; Bidez, M. W. Mechanical properties of trabecular bone in the human mandible: implications for dental implant treatment planning and surgical placement. *Journal of oral and maxillofacial surgery* **1999**, *57* (6), 700-706.

(44) Burstein, A. H.; Reilly, D. T.; Martens, M. Aging of bone tissue: mechanical properties. *JBJS* **1976**, *58* (1), 82-86.

(45) Renders, G.; Mulder, L.; Van Ruijven, L.; Van Eijden, T. Porosity of human mandibular condylar bone. *Journal of anatomy* **2007**, *210* (3), 239-248.

(46) Lekholm, U. Patient selection and preparation. *Tissue-integrated protheses: osseointegration in clinical dentistry* **1985**, 199-209.

(47) Goiato, M. C.; Dos Santos, D.; Santiago, J. J.; Moreno, A.; Pellizzer, E. P. Longevity of dental implants in type IV bone: a systematic review. *International journal of oral and maxillofacial surgery* **2014**, *43* (9), 1108-1116.

(48) Eriksson, R.; Adell, R. Temperatures during drilling for the placement of implants using the osseointegration technique. *Journal of Oral and Maxillofacial Surgery* **1986**, *44* (1), 4-7.

(49) Flanagan, D. Osteotomy irrigation: is it necessary? *Implant Dent* **2010**, *19* (3), 241-249. DOI: 10.1097/ID.0b013e3181dc9852.

(50) Möhlhenrich, S.; Modabber, A.; Steiner, T.; Mitchell, D.; Hölzle, F. Heat generation and drill wear during dental implant site preparation: systematic review. *British Journal of Oral and Maxillofacial Surgery* **2015**, *53* (8), 679-689.

(51) Harder, S.; Egert, C.; Freitag-Wolf, S.; Mehl, C.; Kern, M. Intraosseous Temperature Changes During Implant Site Preparation: In Vitro Comparison of Thermocouples and Infrared Thermography. *International Journal of Oral & Maxillofacial Implants* **2018**, *33* (1).

(52) Bulloch, S. E.; Olsen, R. G.; Bulloch, B. Comparison of heat generation between internally guided (cannulated) single drill and traditional sequential drilling with and without a drill guide for dental implants. *Int J Oral Maxillofac Implants* **2012**, *27* (6), 1456-1460.

(53) Benington, I. C.; Biagioni, P. A.; Briggs, J.; Sheridan, S.; Lamey, P. J. Thermal changes observed at implant sites during internal and external irrigation. *Clinical oral implants research* **2002**, *13* (3), 293-297.

(54) Eriksson, R. A.; Adell, R. Temperatures during drilling for the placement of implants using the osseointegration technique. *J Oral Maxillofac Surg* **1986**, *44* (1), 4-7. DOI: 10.1016/0278-2391(86)90006-6.

(55) Gehrke, S. A.; Neto, H. L.; Mardegan, F. E. Investigation of the effect of movement and irrigation systems on temperature in the conventional drilling of cortical bone. *British Journal of Oral and Maxillofacial Surgery* **2013**, *51* (8), 953-957.

(56) Matthews, L. S.; Hirsch, C. Temperatures measured in human cortical bone when drilling. *JBJS* **1972**, *54* (2), 297-308.

(57) Rashad, A.; Kaiser, A.; Prochnow, N.; Schmitz, I.; Hoffmann, E.; Maurer, P. Heat production during different ultrasonic and conventional osteotomy preparations for dental implants. *Clin Oral Implants Res* **2011**, *22* (12), 1361-1365. DOI: 10.1111/j.1600-0501.2010.02126.x.

(58) Reingewirtz, Y.; Szmukler-Moncler, S.; Senger, B. Influence of different parameters on bone heating and drilling time in implantology. *Clinical oral implants research* **1997**, *8* (3), 189-197.

(59) Jochum, R. M.; Reichart, P. A. Influence of multiple use of Timedur®-titanium cannon drills: thermal response and scanning electron microscopic findings. *Clinical oral implants research* **2000**, *11* (2), 139-143.

(60) Cardemil, C.; Ristevski, Z.; Alsén, B.; Dahlin, C. Influence of different operatory setups on implant survival rate: a retrospective clinical study. *Clin Implant Dent Relat Res* **2009**, *11* (4), 288-291. DOI: 10.1111/j.1708-8208.2008.00123.x.

(61) Ericsson, I.; Nilner, K.; Klinge, B.; Glantz, P. O. Radiographical and histological characteristics of ssubmerged and nonsubmerged titanium implants. An experimental study in the Labrador dog. *Clinical Oral Implants Research* **1996**, *7* (1), 20-26.

(62) Bashutski, J. D.; D'Silva, N. J.; Wang, H. L. Implant compression necrosis: current understanding and case report. *Journal of periodontology* **2009**, *80* (4), 700-704.

(63) Ramesh, R.; Sasi, A.; Mohamed, S. C.; Joseph, S. P. “Compression Necrosis”–A Cause of Concern for Early Implant Failure? Case Report and Review of Literature. *Clinical, Cosmetic and Investigational Dentistry* **2024**, 43-52.

(64) Trisi, P.; Todisco, M.; Consolo, U.; Travaglini, D. High versus low implant insertion torque: a histologic, histomorphometric, and biomechanical study in the sheep mandible. *International Journal of Oral & Maxillofacial Implants* **2011**, *26* (4).

(65) Trisi, P.; Berardini, M.; Falco, A.; Vulpiani, M. P. Effect of Temperature on the Dental Implant Osseointegration Development in Low-Density Bone: An: In Vivo: Histological Evaluation. *Implant dentistry* **2015**, *24* (1), 96-100.

(66) Ercoli, C.; Funkenbusch, P. D.; Lee, H. J.; Moss, M. E.; Graser, G. N. The influence of drill wear on cutting efficiency and heat production during osteotomy preparation for dental implants: a study of drill durability. *Int J Oral Maxillofac Implants* **2004**, *19* (3), 335-349.

(67) Di Fiore, A.; Sivolella, S.; Stocco, E.; Favero, V.; Stellini, E. Experimental analysis of temperature differences during implant site preparation: continuous drilling technique versus intermittent drilling technique. *Journal of Oral Implantology* **2018**, *44* (1), 46-50.

(68) Sabeva, E. Factors Affecting Bone Temperature Increase During Implant Surgery-Review. *Scripta Scientifica Medicinae Dentalis* **2019**, *5* (1), 7-15.

(69) Stelzle, F.; Frenkel, C.; Riemann, M.; Knipfer, C.; Stockmann, P.; Nkenke, E. The effect of load on heat production, thermal effects and expenditure of time during implant site preparation–an experimental ex vivo comparison between piezosurgery and conventional drilling. *Clinical oral implants research* **2014**, *25* (2), e140-e148.

(70) Raj, R.; Manju, V.; Kumar-Gopal, V.; Eswar, M. Analysis of factors determining thermal changes at osteotomy site in dental implant placement-An in-vitro study. *Journal of Clinical and Experimental Dentistry* **2021**, *13* (3), e234.

(71) Lajolo, C.; Valente, N. A.; Romandini, W. G.; Petruzzi, M.; Verdugo, F.; D'Addona, A. Bone heat generated using conventional implant drills versus piezosurgery unit during apical cortical plate perforation. *Journal of Periodontology* **2018**, *89* (6), 661-668.

(72) Lamazza, L.; Garreffa, G.; Laurito, D.; Lollobrigida, M.; Palmieri, L.; De Biase, A. Temperature values variability in piezoelectric implant site preparation: Differences between cortical and corticocancellous bovine bone. *BioMed research international* **2016**, *2016* (1), 6473680.

(73) Augustin, G.; Davila, S.; Udiljak, T.; Vedrina, D. S.; Bagatin, D. Determination of spatial distribution of increase in bone temperature during drilling by infrared thermography: preliminary report. *Archives of Orthopaedic and Trauma Surgery* **2009**, *129*, 703-709.

(74) Yacker, M. J.; Klein, M. The effect of irrigation on osteotomy depth and bur diameter. *Int J Oral Maxillofac Implants* **1996**, *11* (5), 634-638.

(75) Benington, I.; Biagioni, P.; Crossey, P.; Hussey, D.; Sheridan, S.; Lamey, P.-J. Temperature changes in bovine mandibular bone during implant site preparation: an assessment using infra-red thermography. *Journal of dentistry* **1996**, *24* (4), 263-267.

(76) Augustin, G.; Davila, S.; Mihoci, K.; Udiljak, T.; Vedrina, D. S.; Antabak, A. Thermal osteonecrosis and bone drilling parameters revisited. *Arch Orthop Trauma Surg* **2008**, *128*, 71-77.

(77) Lavelle, C.; Wedgwood, D. Effect of internal irrigation on frictional heat generated from bone drilling. *Journal of oral surgery (American Dental Association: 1965)* **1980**, *38* (7), 499-503.

(78) Sindel, A.; Dereci, Ö.; Hatipoğlu, M.; Altay, A.; Özalp, Ö.; Öztürk, A. The effects of irrigation volume to the heat generation during implant surgery. *Medicina oral, patologia oral y cirugia bucal* **2017**, *22* (4), e506.

(79) Gehrke, S. A.; Pazetto, M. K.; de Oliveira, S.; Corbella, S.; Taschieri, S.; Mardegan, F. E. Study of temperature variation in cortical bone during osteotomies with trephine drills. *Clinical oral investigations* **2014**, *18*, 1749-1755.

(80) Strbac, G. D.; Unger, E.; Donner, R.; Bijak, M.; Watzek, G.; Zechner, W. Thermal effects of a combined irrigation method during implant site drilling. A standardized in vitro study using a bovine rib model. *Clinical oral implants research* **2014**, *25* (6), 665-674.

(81) Strbac, G. D.; Giannis, K.; Unger, E.; Mittlböck, M.; Watzek, G.; Zechner, W. A novel standardized bone model for thermal evaluation of bone osteotomies with various irrigation methods. *Clinical oral implants research* **2014**, *25* (5), 622-631.

(82) Barrak, I.; Joób-Fancsaly, A.; Varga, E.; Boa, K.; Piffko, J. Effect of the Combination of low-speed drilling and cooled irrigation fluid on intraosseous heat generation during guided surgical implant site preparation: An: In vitro: Study. *Implant dentistry* **2017**, *26* (4), 541-546.

(83) Misir, A. F.; Sumer, M.; Yenisey, M.; Ergioglu, E. Effect of surgical drill guide on heat generated from implant drilling. *Journal of Oral and Maxillofacial Surgery* **2009**, *67* (12), 2663-2668.

(84) dos Santos, P. L.; Pereira Queiroz, T.; Margonar, R.; de Souza Carvalho, A. C. G.; Betoni Jr, W.; Rodrigues Rezende, R. R.; dos Santos, P. H.; Rangel Garcia Jr, I. Evaluation of bone heating, drill deformation, and drill roughness after implant osteotomy: guided surgery and classic drilling procedure. *International Journal of Oral & Maxillofacial Implants* **2014**, *29* (1).

(85) Barrak, I.; Joób-Fancsaly, Á.; Braunitzer, G.; Varga Jr, E.; Boa, K.; Piffkó, J. Intraosseous Heat Generation During Osteotomy Performed Freehand and Through Template With an Integrated Metal Guide Sleeve: An: In Vitro: Study. *Implant dentistry* **2018**, *27* (3), 342-350.

(86) Barrak, I.; Boa, K.; Joób-Fancsaly, Á.; Varga, E.; Sculean, A.; Piffkó, J. Heat generation during guided and freehand implant site preparation at drilling speeds of 1500 and 2000 RPM at different irrigation temperatures: an in vitro study. *Oral Health Prev Dent* **2019**, *17* (4), 309-316.

(87) Misic, T.; Markovic, A.; Todorovic, A.; Colic, S.; Miodrag, S.; Milicic, B. An in vitro study of temperature changes in type 4 bone during implant placement: bone condensing versus bone drilling. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* **2011**, *112* (1), 28-33. DOI: 10.1016/j.tripleo.2010.08.010.

(88) Tuijthof, G.; Frühwirt, C.; Kment, C. Influence of tool geometry on drilling performance of cortical and trabecular bone. *Medical engineering & physics* **2013**, *35* (8), 1165-1172.

(89) Wiggins, K.; Malkin, S. Drilling of bone. *Journal of biomechanics* **1976**, *9* (9), 553-559.

(90) Chacon, G. E.; Bower, D. L.; Larsen, P. E.; McGlumphy, E. A.; Beck, F. M. Heat production by 3 implant drill systems after repeated drilling and sterilization. *J Oral Maxillofac Surg* **2006**, *64* (2), 265-269. DOI: 10.1016/j.joms.2005.10.011.

(91) Scarano, A.; Piattelli, A.; Assenza, B.; Carinci, F.; Di Donato, L.; Romani, G. L.; Merla, A. Infrared thermographic evaluation of temperature modifications induced during implant site preparation with cylindrical versus conical drills. *Clin Implant Dent Relat Res* **2011**, *13* (4), 319-323. DOI: 10.1111/j.1708-8208.2009.00209.x.

(92) Allan, W.; Williams, E.; Kerawala, C. Effects of repeated drill use on temperature of bone during preparation for osteosynthesis self-tapping screws. *British Journal of Oral and Maxillofacial Surgery* **2005**, *43* (4), 314-319.

(93) Oliveira, N.; Alaejos-Algarra, F.; Mareque-Bueno, J.; Ferrés-Padró, E.; Hernández-Alfaro, F. Thermal changes and drill wear in bovine bone during implant site preparation. A comparative in vitro study: twisted stainless steel and ceramic drills. *Clin Oral Implants Res* **2012**, *23* (8), 963-969. DOI: 10.1111/j.1600-0501.2011.02248.x.

(94) Allsobrook, O. F.; Leichter, J.; Holborrow, D.; Swain, M. Descriptive study of the longevity of dental implant surgery drills. *Clin Implant Dent Relat Res* **2011**, *13* (3), 244-254. DOI: 10.1111/j.1708-8208.2009.00205.x.

(95) Branemark, P.-I. Osseointegrated implants in the treatment of the edentulous jaw: experience from a 10-year period. *Scad J Plast Reconstr Surg* **1977**, *16*, 1-132.

(96) Branemark, P. I.; Adell, R.; Breine, U.; Hansson, B. O.; Lindstrom, J.; Ohlsson, A. Intra-osseous anchorage of dental prostheses. I. Experimental studies. *Scand J Plast Reconstr Surg* **1969**, *3* (2), 81-100. DOI: 10.3109/02844316909036699 From NLM Medline.

(97) Soldatos, N.; Pham, H.; Fakhouri, W. D.; Ngo, B.; Lampropoulos, P.; Tran, T.; Weltman, R. Temperature Changes during Implant Osteotomy Preparations in Human Cadaver Tibiae Comparing MIS. *Genes (Basel)* **2022**, *13* (10). DOI: 10.3390/genes13101716.

(98) Augustin, G.; Zigman, T.; Davila, S.; Udilljak, T.; Staroveski, T.; Brezak, D.; Babic, S. Cortical bone drilling and thermal osteonecrosis. *Clin Biomech (Bristol, Avon)* **2012**, *27* (4), 313-325. DOI: 10.1016/j.clinbiomech.2011.10.010.

CHAPTER 2

Manuscript

Temperature Changes (ΔT) in Correlation with Number of Implant Osteotomy Preparations in Human Cadaver Tibiae, Comparing Osseodensification (OD) Burs in Clockwise (CW) versus Counterclockwise (CCW) Mode

Abstract: (1) Background: OD burs are used in two different modes; (i) CW and (ii) CCW. The purpose of the study was to evaluate the ΔT during the preparation of implant osteotomies, in a four-way interaction. (2) Methods: Three hundred sixty osteotomies were prepared at 12 mm depth in human cadaver tibiae. ΔT were calculated similarly to two previous studies of our group. Four different variables were evaluated for their effect on ΔT. (3) Results: A four-way interaction was observed in the CCW mode, allowing 1000 RPM to have the least effect in both modes. However, in CCW mode the use of 3.0 and 4.0 burs after 23 osteotomies showed a statistically significant increase of ΔT, and significant chatter, compared to CW mode. In the CCW mode, ΔT was increased significantly as the diameter of the burs increased in 800 and 1200 RPM. (4) Conclusions: The synergistic effect of drills' diameter, CCW mode, 800 and 1200 RPM, and bur usage (over 23 times) had a significant effect on ΔT, which exceeded 47^0C. One thousand (1000) RPM had the least effect in both modes. The 3.0 and 4.0 burs in CCW mode significantly increased the temperature and produced significant chatter.

Keywords: temperature changes, clockwise mode, counterclockwise mode, osseodensification burs, cortical bone; cancellous bone; human cadaver tibiae, chatter, dental implants.

Introduction

Initial biomechanical primary stability of dental implants is of paramount importance for osseointegration and long-term success. [1] Factors considered affecting primary stability are the implant thread type and surface, the bone mineral density and type, and the surgical protocol. [2-6] Traditional surgical techniques for osteotomy preparation utilize undersized drilling protocols providing increased bone to implant contact yielding higher insertion torque values. [7]

The concept of OD was introduced with the aim of creating a layer of compacted autogenous bone along the surface of an implant osteotomy, increasing primary implant stability, bone mineral density, and the percentage of bone to implant contact. [8] OD protocol utilizes specially designed burs (Densah® burs) with cutting, chiseled edges to develop the length of the osteotomy and a tapered shaft with non-cutting edges to compact the bone laterally and progressively increase the diameter of the osteotomy. The CCW rotation along with copious irrigation allows for hydraulic compression along the periphery of the osteotomy. [8] Histologic analysis of osteotomy sites created with the use of these burs confirm circumferential compaction of alveolar bone and autographing through the appearance of new bone growth on bone chips embedded at the periphery of the osteotomies. [9] Other protocols in implant dentistry where the OD burs can be used in a CCW mode are the ridge expansion, placement of immediate implants, placement of zygoma implants, and molar septum expansion with or without the placement of an immediate implant. The versatility of the OD burs extends to use in CW mode, where traditional implant osteotomies can be prepared similar to conventional implant drills. Interestingly, studies comparing bone mineral density, insertion and removal torque values, and percent bone to implant contact between CCW or CW modes with OD burs or manufacturer specific drills and drilling protocols in implant dentistry, showed statistically superior values in all comparisons with both modes using OD burs over conventional drilling protocols. [9-11]

Peri-implant bone loss during the initial healing period and while the implant is still submerged, is linked to surgical trauma during the preparation of the osteotomy or implant placement. [12-14] Factors that may influence the bone overheating are bone density, drilling sequence, the design of the drills, the use of external or internal irrigation, the pressure applied to the handpiece from the operator and the number of times the drills were used. [15-25]

In 2022, the independent and synergistic effect of drill design, diameter, and specific RPM was reported from our group, to significantly raise the temperature during CW osteotomy preparations with straight drills and OD burs. [26] The greatest temperature changes occurred early in the osteotomy preparation. As the OD bur diameter increased, the ΔT decreased. The initial pilot bur, in the OD group, produced the greatest temperature change of 4^0C, 5^0C, and 6^0C at 1000, 1200, 800 RPM, respectively. One thousand (1000) RPM, shown in both conventional drills and OD burs, has less effect in ΔT, compared to 800 and 1200 RPM. The magnitude of the increased temperature readings throughout the osteotomy process did not exceed the critical threshold of 47^0C, which could lead to necrosis of the alveolar bone, impairment of bone healing which could compromise the implant osseointegration. [26]

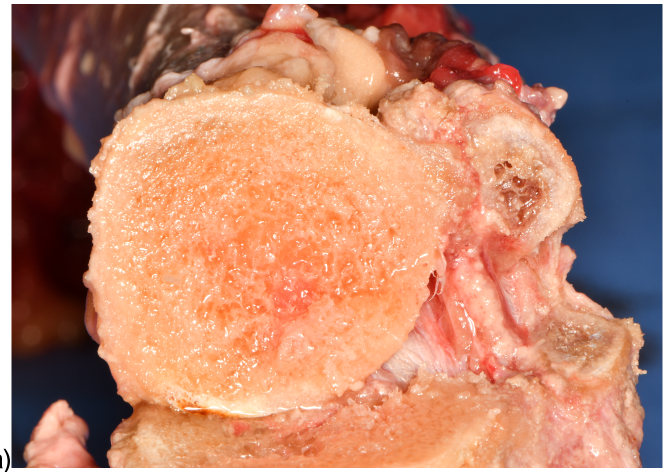
Bhargava et al. [27] compared temperature changes and bone architecture following osteotomy preparations with osteotomes, piezoelectric technology, with the use of OD burs in the CCW rotation, and conventional drilling. The drilling protocols were carried out at 1100 RPM. The temperature changes were calculated by subtracting the temperature readings prior to initiating the drilling sequences from the temperature readings at the completion of the drilling sequences. The piezoelectric and OD processes increased temperatures by 5^0C and 1^0C, respectively within the cortical bone core of the porcine rib specimens with negligible changes from the other 2 techniques. Within the cancellous bone levels, the piezoelectric technique registered slightly less temperature increases, while the OD and other techniques registered minimum to no changes in temperature. [27]

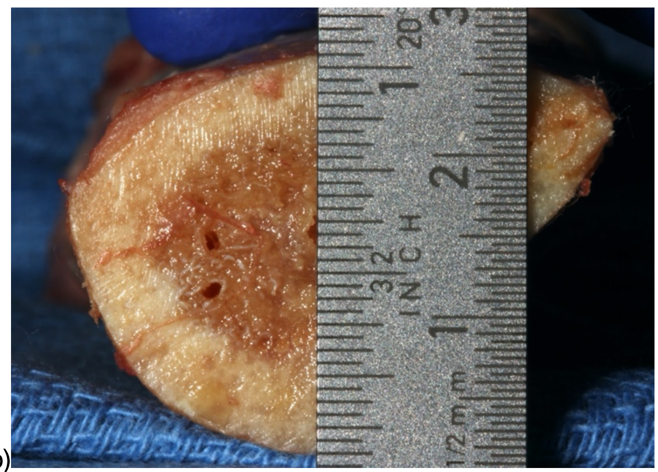
The purpose of the present study was to assess the effect on ΔT during the preparation of 60 implant osteotomies per group, in a four-way interaction: (i) CW compared to CCW mode, (ii) three different RPM (800, 1000 and 1200), (iii) drill diameter, and (iv) usage of OD burs. The null hypotheses were: (i) the CW and CCW use of OD burs will produce the same amount of heat generation in every RPM, and (ii) using the burs 60 times per group will result in the same amount of heat generation in every RPM and mode.

Materials and methods

No institutional review board (IRB) approval was required for the completion of the present human cadaver study. The OHSU IRB reviews research that involves human subjects. Cadavers are not considered human subjects. The cadavers were de-identified, and the four examiners (N.S., A.H., S.S., and L.H.) could not identify the subjects. The cadavers were donated for clinical and research purposes to the cadaver donation and VirtuOHSUÒ simulation and surgical training center at the Richard T. Jones Hall for Basic Medical Sciences, in Portland, Oregon. The relatives signed all the appropriate informed consents, and the cadavers were examined through blood testing to ensure the safety of the present study. The methodology was reviewed and approved by an independent statistician. Three unembalmed cadavers (two male and one female) were used in the present study. All three cadavers were between 77-79 years old and were deceased from December 2021 until January 2022. The causes of deaths were pulmonary fibrosis, respiratory failure, and ovarian cancer, respectively. All three cadavers were freshly frozen and stored at 5°F. The cadavers were placed in a cooler at 42^0F to thaw for 3 days, prior to the beginning of the present study. The study took place in February 2022.

Human mandibular and tibial bones, although having different origins, have similar mechanical properties such as compressive strength and modulus of elasticity. [28] An innovative translational model using human cadaver tibiae, under the plateau, was used in the present study. The model was previously developed and validated by one of the authors (N.S.) and has already been used in two previous studies. [26,29] Six, six-inch-long unembalmed tibial sections were harvested bilaterally from all three cadavers and placed in water baths, similar to the previous studies of our group. [26,29]

(1a)


(1b)


Figures 1a, 1b. Two **t**ibial sections under the plateau, with 5 mm cortical and 7 mm cancellous bone, right after harvesting.

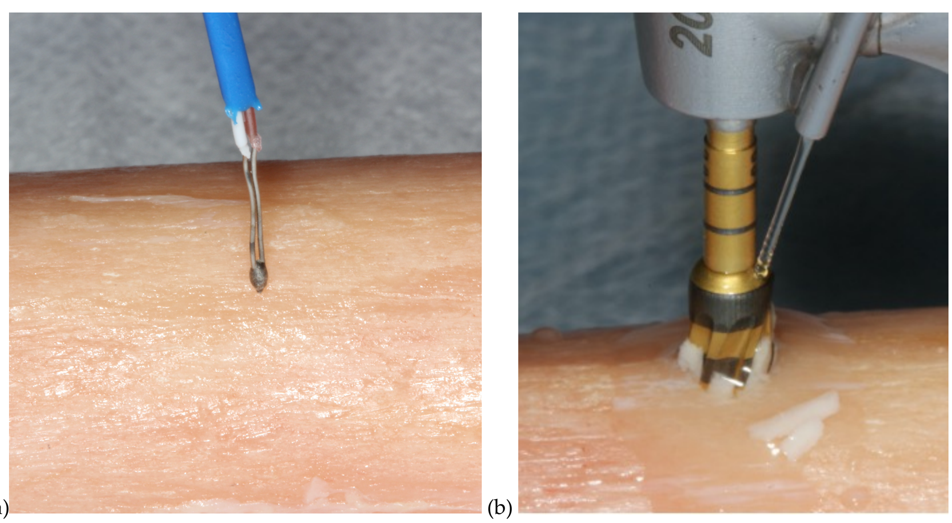
Three temperature regulated digital laboratory water baths (IVYX Scientific, Seattle, WA, USA), filled with sterile saline, were maintained at a range of 95.2°F to 99.6°F (35.1-37.5 °C), to simulate normal-physiologic human body temperature. The room temperature was kept at a constant 68 ± 1°F (20 °C).

The study design allowed for the preparation of 60 osteotomies per group, using OD burs. The length of each osteotomy was 12 mm (5 mm cortical and 7 mm cancellous bone). The temperature of the tibiae and the osteotomies were recorded with a K-type thermocouple (Fisher Scientific®, Hampton, NH, USA 15-078-187, range −58 to 2000 °F, resolution 0.1°/1°, sampling rate 2.5 times per second), with an ultra-fast response naked bead probe (maximum range 260°C), respectively. [26,29] The thermocouple was programmed to measure the maximum temperature during the preparation of the osteotomies. Figures 1a and 1b, show two tibial sections, right after harvesting. These tibiae are an accurate representation of the six tibial sections used in the study. The OD burs used for the preparation of the osteotomies were donated by Versah® LLC (Jackson, MI, USA). The bur sequence of the manufacturer for the placement of a 5.0x12mm bone level implant (burs 1.6, 2.0, 2.3, 2.5, 3.0, 4.0, and 4.3), was followed for all groups (Figure 2).

Figure 2. The bur sequence protocol (1.6, 2.0, 2.3, 2.5, 3.0, 4.0, and 4.3) is used for the preparation of osteotomies in every group, according to manufacturer's recommendations for a 5.0x12 mm bone level implant.

Six groups were formed: three for CW (800-1000-1200 RPM) and three for CCW (800-1000-1200 RPM). For each group, a new set of burs was used. Four examiners (N.S., A.H., S.S., and L.H.) were working on the preparation of the osteotomies, therefore they were previously calibrated to avoid any inconsistency during data collection.

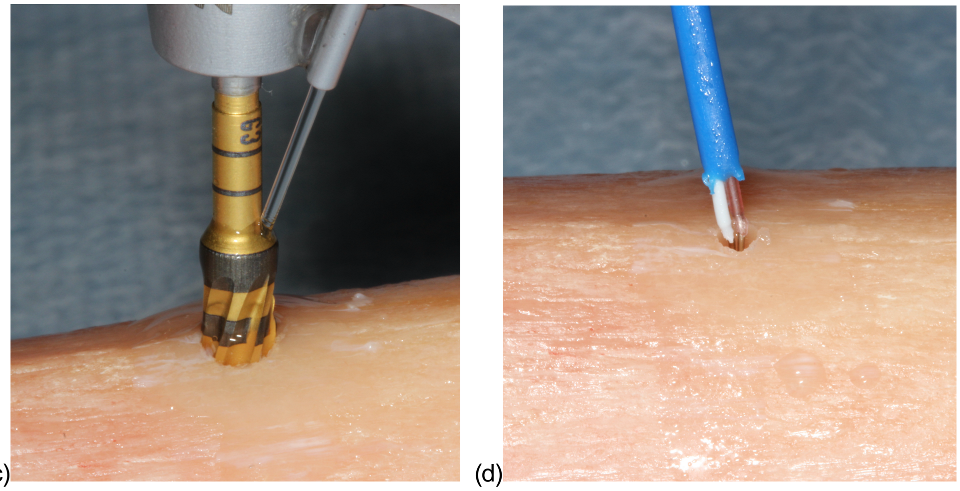
Calibration: Calibration of the examiners was completed using a protocol previously described in two studies of our group. [26,29] The examiners (N.S., A.H., S.S., and L.H.) were rotating every 5 osteotomies, between CW and CCW groups. The tibial sections were removed from the water bath and placed on a countertop. A baseline temperature measurement was recorded on the osseous surface prior to preparation. Implant osteotomy preparations were performed either in CW or CCW mode. Then, the probe was inserted into the osteotomies' walls, immediately following the osteotomy preparation with each consecutive drill and the temperature was measured and recorded. (Figures 3a-3d).



(a) (b)

Figure 3a. The thermocouple probe recording a baseline temperature at the osseous surface.

Figure 3b. CW implant osteotomy preparation with external irrigation. Note the characteristic bone chips trapped during drilling at the flutes of the bur.



(c) (d)

Figure 3c. CCW implant osteotomy preparation with external irrigation. The characteristic bone chips trapped at the flutes of the bur, seen previously at CW preparation, are absent since the bone is densified over the walls of the osteotomy.

Figure 3d. The thermocouple probe recording the maximum temperature over the walls of the osteotomy.

ΔT was calculated by subtracting the baseline temperature from the maximum temperature recorded immediately after drilling for each drill diameter (ΔT = Tmax – Tbaseline). After 2-3 osteotomies, the tibial sections were returned to the water baths to maintain the temperature as close to human body temperature within the bounds of study protocol. To allow the dispersed heat to dissipate before another osteotomy was performed, consecutive osteotomies were performed on opposite ends of the tibial sections. Sixty (60) osteotomies were prepared, at 12 mm depth per group, to allow for a total of 360 osteotomies. All values were recorded on an Excel® (Redmond, WA, USA) spreadsheet.

Statistical analyses: For the statistical analyses, the R statistical software was used (R Core Team 2021, R Foundation for Statistical Computing, Vienna, Austria). [30] The variables [(i) mode; CW compared to CCW, (ii) RPM, (iii) drill diameter, and (iv) usage number of OD burs] were evaluated both for their individual and for their synergistic effect on ΔT with the use of one-, two-, three-, and four-way interactions.

Results

Table 1, figures 4 and 5, demonstrate the results of the present study. Table 1 shows a four-way interaction between the variables and ΔT. All the variables independently and synergistically had a significant impact on ΔT. There was a statistically significant difference between CW and CCW modes.

	DF	SumSq	Mean Sq	F value	Pr(>F)
U	1	7808	7808	209.270	< 2e-16 ***
M	1	31757	31757	851.198	< 2e-16 ***
DW	5	11741	2348	62.942	< 2e-16 ***
RPM	2	24320	12160	325.923	< 2e-16 ***
U:M	1	4321	4321	115.826	< 2e-16 ***

U:DW	5	1732	346	9.285	9.30e-09 ***
M:DW	5	13320	2664	71.404	< 2e-16 ***
U:RPM	2	3889	1944	52.119	< 2e-16 ***
M:RPM	2	3650	1825	48.921	< 2e-16 ***
DW:RPM	10	4670	467	12.518	< 2e-16 ***
U:M:DW	5	1819	364	9.750	3.20e-09 ***
U:M:RPM	2	1614	807	21.631	5.03e-10 ***
U:DW:RPM	10	1943	194	5.208	1.39e-07 ***
M:DW:RPM	10	3720	372	9.970	< 2e-16 ***
U:M:DW:RPM	10	2083	208	5.584	2.89e-08 ***

*** Indicates statistical significance < 0.0001

Table 1. ANOVA table shows a four-way interaction between the variables and ΔT. *[Abbreviations used in the table: U (Use), M (Mode), DW (Drill Width)]*

Figure 4 illustrates both modes, all three RPM and use of the burs. At the CCW mode and at 800 and 1200 RPM, the ΔT was significantly affected and raised over the critical threshold of 47^0C. The use of burs at 1000 RPM had the least effect on ΔT in both modes. The first chatter was evident after 23 and 26 osteotomies in 1200 and 800 RPM respectively, at the CCW mode, as a type of vibration during the drilling process which led to inaccurate drilling depth, compromised stability of the implant site, and damage to surrounding bone tissue. The chatter allowed the ΔT to go as high as 68^0C, and the overall temperature at 98.1^0C. No chatter was noted at the CW mode.

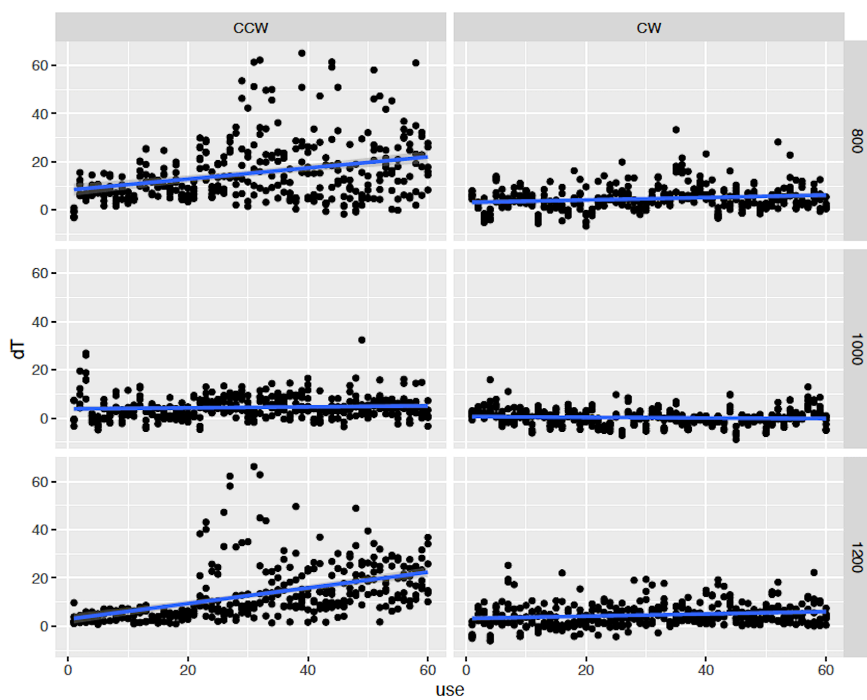


Figure 4. View of both modes, ΔT, three different RPM and number of osteotomies. At the CCW mode, the ΔT was significantly affected and raised at 800 and 1200 RPM. One thousand RPM, in both modes, had no significant effect in ΔT.

Figure 5 shows that all burs, except 1.6 bur, had chatter at the CCW mode which significantly affected ΔT. The 2.0 bur began to chatter after 32 osteotomies at 1200 RPM. Both 3.0- and 4.0-

mm burs began to chatter after 23 osteotomies. After the evidence of chatter, the burs had consistent high ΔT and high overall temperature up to 60 osteotomies, exceeding the critical threshold of 47⁰C. Two additionally significant findings were (i) the suspension of the 4.3 mm bur from the study after 35 osteotomies in both modes, since it was impossible to latch it into the handpiece, due to a bent shaft and a broken latch, and (ii) the spring back effect on the CCW mode, more noticeable at 1000 RPM. The spring back effect did not allow the placement of the same bur back into the osteotomy, after the completion of the preparation.

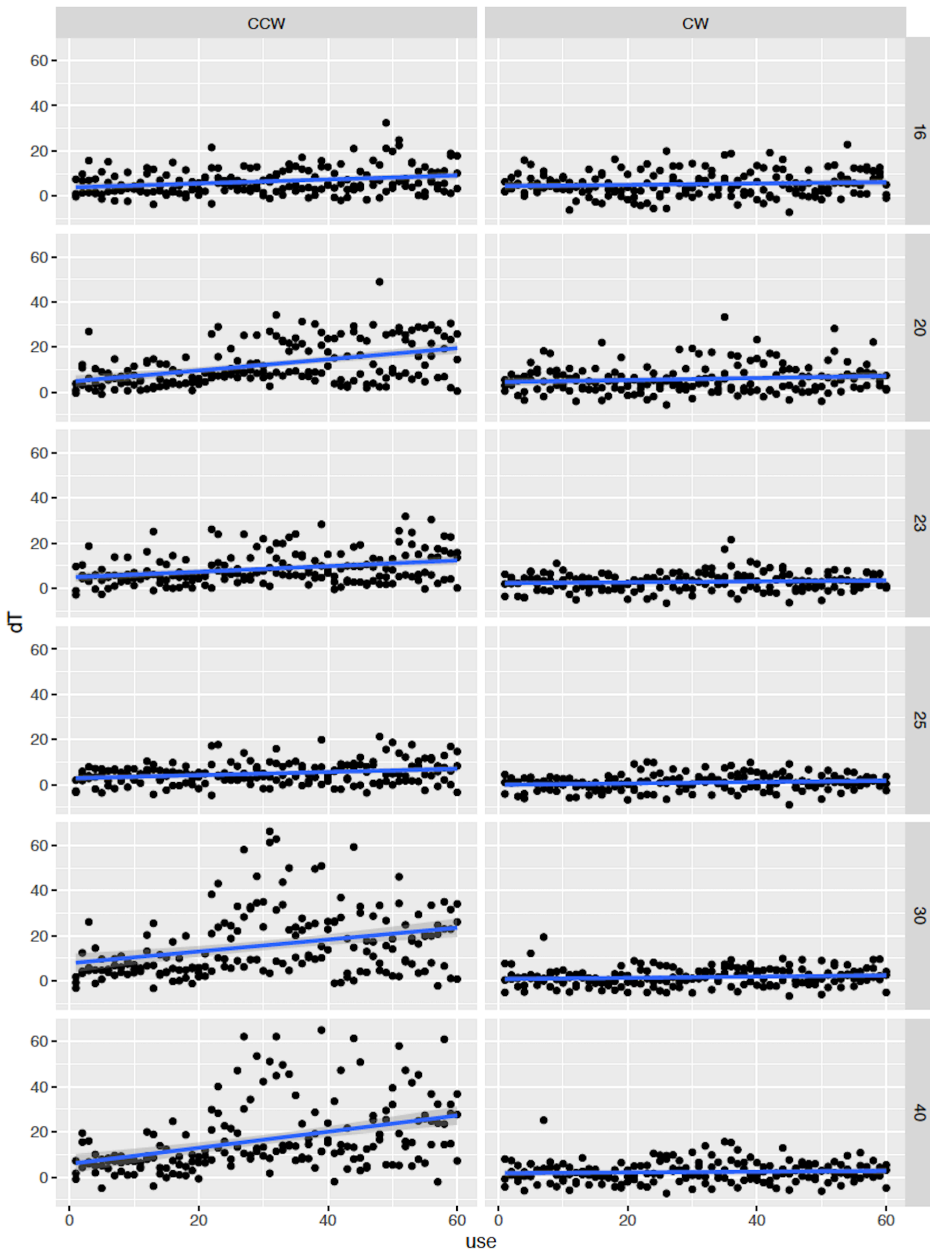
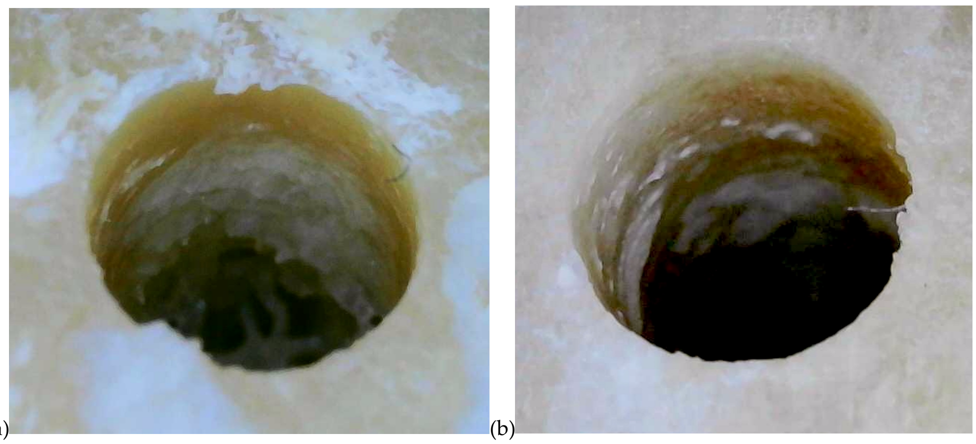


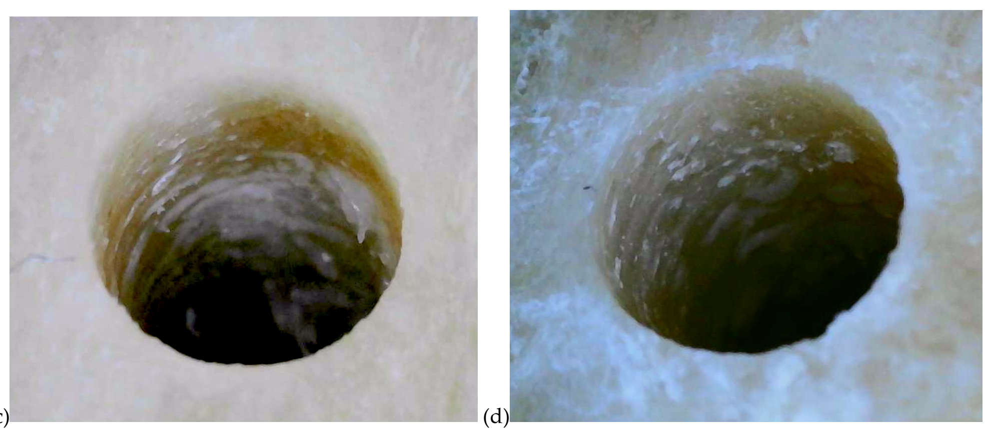
Figure 5. View of the CW and CCW modes along with the number of osteotomies and the burs used, based on the manufacturer's protocol. The 2.0 bur began to chatter after 32 osteotomies at 1200 RPM. Both 3.0- and 4.0-mm burs began to chatter after 23 osteotomies allowing for consistent high ΔT and high overall temperature which exceeded the critical threshold of 47⁰C.

Stereoscopy imaging: Stereoscopy imaging was performed similar to Soldatos et al. in 2022. [26] A separate tibial section was used for the preparation of six osteotomies with the use of OD burs: (i) CW-CCW at 800 RPM, (ii) CW-CCW at 1000 RPM, and (iii) CW-CCW at 1200 RPM (Figures 6a-6f). The tibial section with the six osteotomies was submerged in sterile water before taking stereomicroscopic images. The submerged sections were then placed under the objective lens of a Nikon® Stereomicroscope SMZ 800 (Melville, NY, USA), and images were taken at 40x magnifications. The specimen with the 1000 RPM CCW mode showed the most densified bone compared to 800 and 1200 RPM. CW mode in all three different RPM, showed similar irregularities over the osteotomy walls (except for 1000 RPM), suggesting uncondensed bone. The specimen with the 1000 RPM CW mode, was in accordance with the results of the present study, showing a mixed condensed and uncondensed bone.



(a) (b)

Figure 6a, 6b. View of **s**tereoscopy imaging of CW (a) and CCW (b) modes at 800 RPM.



(c) (d)

Figure 6c, 6d. View of **s**tereoscopy imaging of CW (c) and CCW (d) modes at 1000 RPM. Note the optimum OD at the CCW mode, compared to 800 and 1200 RPM.

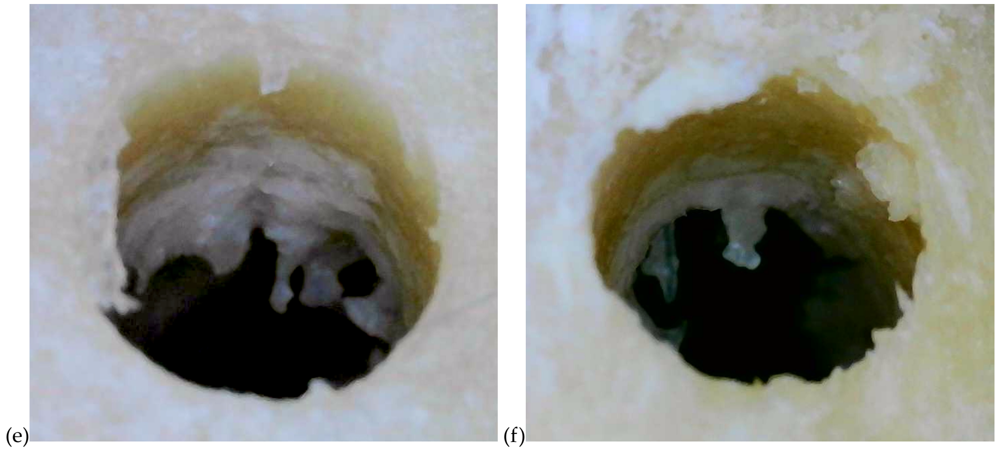


Figure 6e, 6f. View of **s**tereoscopy imaging of CW(e) and CCW (f) modes at 1200 RPM.

Discussion

The present study compared multiple variables at one time; similar to what would be addressed in a clinical environment. The purpose was to assess the effect on ΔT during the preparation of 60 implant osteotomies in a four-way interaction: (i) CW compared to CCW mode, (ii) three different RPM (800, 1000 and 1200), (iii) drill diameter, and (iv) usage of OD burs. Both null hypotheses were rejected since there was a statistically significant difference between the CW and CCW mode in all RPM (except 1000 RPM), the drill size had a significant effect and, using the burs more than 23 times significantly elevated the temperature (over 47^{0}C) which subsequently significantly affected the ΔT. One thousand (1000) RPM had the least effect on ΔT in both modes, confirming previous study findings. [26] The critical temperature point, which can compromise the bone around an implant, was described at >47^{0}C for one minute, since it has significantly reduced the bone formation around implants. [31,32] In order to measure the temperature, a K-type thermocouple measuring unit was utilized in the present study due to higher accuracy through a liquid medium, compared to infrared thermography. [33-35] The measurement of the temperature was performed directly into the osteotomy since it was reported that there is a 1.5^{0}C difference in temperature between distances of 0.3 mm and 0.5 mm from the osteotomy site. [36] The CW results of the present study are in accordance with Soldatos et al. 2022 [26], where the same burs were used to prepare 40 osteotomies in the same human cadaver model.

The present study and previous studies from the same group used a high translational human cadaver model using the tibial bone under the plateau. However, several studies have been performed in bone substitutes. The model of the present study had 5 mm cortical and 7 mm cancellous bone. Cortical and cancellous bone have different healing responses and heat dispersal during osteotomy preparations, since there is anatomical variance between them. [37] In addition, the porosity of the alveolar bone differs between cortical (3.5%) and cancellous bone (79.3%). [38] The bone substitutes are solid rigid polyurethane foam bone blocks, used as an alternative test medium for human bone (Sawbones®, Vashon Island, WA, USA). This type of bone was used for calibration in the present study and the previous study of our group. [39,40] Romeo et al. [11], on artificial bone substitutes focused on the use of OD and conventional burs in CW and CCW modes, and their relationship to implant stability measurements, obtained by insertion torque and resonance frequency analysis. They found that the OD burs in the CCW mode allowed for significantly higher insertion and removal torque of bone level tapered implants. However, 600 RPM was used for all burs, which is not recommended by the manufacturers of both the OD and the conventional burs. In addition, they noticed that the final diameter of the osteotomy created with the OD burs in CCW, was narrower than the other drilling modalities due to the spring-back effect of the cancellous bone after drilling, a finding that was noticed in the present study as well.

[11] The spring back effect was described by Kold et al. [41], as a response of compacted bone which reduces the size of the osteotomy. [41] Huwais and Meyer [42] reported, in a porcine tibial model, that the spring back effect is due to the viscoelastic portion of the deformation causing a 91% reduction of the OD osteotomy size, when it was left empty during microcomputed tomography.[42]

Many studies used different models, different temperature measuring devices, different RPM, different drill designs and location of temperature capture in order to address the temperature changes during implant osteotomy preparations. [26,29,37,40,43-52] All the studies have used drills in CW mode. Trisi et al. [37], found that temperature of 60^0 for 1 min, in an iliac crest sheep model, significantly reduced the bone to implant contact. [37] Dos Santos et al. [43], in a rabbit tibial model, found that guided drilling protocol produced higher temperature than the conventional. The temperature increased with the number of times the drills were used; an opposite finding from the CW mode group of the present study. [43] Similar to Dos Santos et al., Barrak et al. [44], evaluated the intraosseous temperature during guided and free-hand osteotomy preparations. The model and the protocol were different as they used bovine ribs at 800, 1200, 1500, and 2000 RPM. The guided group significantly elevated the temperature over the critical threshold of 47^0C, with the metal sleeve of the guide, the higher RPM, the sterilization protocol of the drills and the number of the osteotomies performed with the same drills, being significant contributing factors to the elevation of the temperature. [44] Matthews and Hirsch [45] in 1972, reported temperatures more than 100^0C, when under laboratory conditions, they drilled human cortical bone without irrigation. In addition, worn drills and the force applied to the drill were more important factors to increase the temperature than the drilling speed. [45] Benington et al. [46], in a bovine mandibular model using the Branemark technique for implant placement, reported temperatures as high as 130.1^0C, when three different drills were used. [46] Three different studies from Misir et al. [47], Jochum et al. [48], Oliveira et al. [49], and Allsobrook et al. [50], described a non-significant elevation of the temperature after the use of drills 50, 40, 50 and 40 times, respectively. [48-51] In the present study, after 60 osteotomies in the CW group, there was no significant elevation of the temperature. Chacon et al. [51] measured the temperature generated by straight design drills using sequential drilling up to 4–4.2 mm diameters. Only the drill design without a relief angle yielded a bone temperature above 47^0C. [51] Scarano et al. [52], found that the triple twist cylinder drills generated more heat than the quadruple twist conical drills on a cortical bovine bone model. [52] Finally, our group discovered a three-way interaction between ΔT and drill design, drill diameter, and RPM. A clear pattern appeared for the OD burs at all RPM, after they were used 40 times in a CW mode. [26]

The chatter reported in the present study in the CCW mode can negatively impact the success of the implant placement procedure by causing irregular bone preparation, and affecting the overall integration and longevity of the implant. Surgical providers aim to minimize chatter by replacing the drills according to manufacturer's recommendations, and using appropriate drill techniques, specific RPM, and equipment to ensure precise and controlled drilling during implant surgery. [53]

The examination of the specimens through stereoscopy imaging proved the OD of the CCW mode (especially in 1000 RPM), as was previously reported. [26] Temperature changes during dental implant osteotomy preparations can have significant effects on the success of the implant surgical procedure. Optimization through proper selection of drilling parameters and use of irrigation are crucial to minimize temperature changes and reduce the risk of complications. To the best of the authors knowledge, this is the first human cadaver study measuring ΔT by comparing the two different modes of the OD burs for the preparation of dental implant osteotomies. The group of authors have identified some limitations of the study, such as (i) the in vitro nature on a fresh human cadaver model which does not account for the blood and salivary flow of a patient, and the real-time in vivo intraosseous bone temperatures, and (ii) if the thermocouple was attached to the implant handpiece, would have allowed for even more accurate temperature measurements.

Conclusions

The synergistic effect of CCW mode, drills' diameter, RPM, and use of the burs over 23 times had a significant effect on ΔT in human cadaver tibiae which exceeded the critical threshold of 47^0C. Significant chatter was produced at almost every bur, in the CCW mode, after using over 23 times. One thousand (1000) RPM had the least effect in both modes.

References

1. Albrektsson T, Brånemark PI, Hansson HA, et al. Osseointegrated titanium implants. Requirements for ensuring a long-lasting, direct bone-to-implant anchorage in man. Acta Orthop Scand. 1981; 52: 155–170.
2. Marquezan M, Osório A, Sant'Anna E, et al. Does bone mineral density influence the primary stability of dental implants? A systematic review. Clin Oral Implants Res. 2012; 23: 767–774.
3. Trisi P, De Benedittis S, Perfetti G, et al. Primary stability, insertion torque and bone density of cylindrical implant ad modum Brånemark: Is there a relationship? An in vitro study. Clin Oral Implants Res. 2011; 22: 567–570.
4. Turkyilmaz I, Aksoy U, McGlumphy EA. Two alternative surgical techniques for enhancing primary implant stability in the posterior maxilla: A clinical study including bone density, insertion torque, and resonance frequency analysis data. Clin Implant Dent Relat Res. 2008; 10: 231–237.
5. Yoon HG, Heo SJ, Koak JY, Kim SK, Lee SY. Effect of bone quality and implant surgical technique on implant stability quotient (ISQ) value. J Adv Prosthodont 2011; 3: 10–15.
6. Ottoni JM, Oliveira ZF, Mansini R, et al. Correlation between placement torque and survival of single-tooth implants. Int J Oral Maxillofac Implants. 2005; 20: 769–776.
7. Capparé P, Vinci R, Di Stefano DA, et al. Correlation between initial BIC and the Insertion Torque/Depth Integral Recorded with an Instantaneous Torque- Measuring Implant Motor: An in vivo Study. Clin implant Dent Relat Res. 2015; 17: 613–620.
8. Huwais S, Meyer EG. A novel osseous densification approach in implant osteotomy preparation to increase biomechanical primary stability, bone mineral density, and bone-to-implant contact. Int J Oral Maxillofac Implants 2017; (32) 1: 27-36.
9. Lahens B, Neiva R, Tovar N, Alifarag AM, Jimbo R,.Bonfante EA, Bowers MM, Cuppini M, Freitas H, Witek L, Coelho PG. Biomechanical and histologic basis of osseodensification drilling for endosteal implant placement in low density bone. An experimental study in sheep. J Mech Behav Biomed Mater. 2016; 83:56-65.
10. Yeh Y-T, Chu T-M G, Blanchard SB, Hamada Y. Effects on ridge dimensions, bone density, and implant primary stability with osseodensification approach in implant osteotomy preparation. Int J Oral Maxillofac Implants 2021; 36:474–484.
11. Romeo D, Chochlidakis K, Barmak AB, Afliardi E, Russo LL, Ercoli C. Insertion and removal torque of dental implants placed using different drilling protocols: An experimental study on artificial bone substitutes. J. Prosthodont. 2023; 32:633–638.
12. Ericsson I, Nilner K, Klinge B, Glantz PO. Radiographical and histological characteristics of submerged and non-submerged titanium implants. An experimental study in the Labrador dog. Clin Oral Implants Res. 1996; 7:20-26.
13. Oh TJ, Yoon J, Misch C, Wang HL. The causes of early implant bone loss: myth or science? J Periodontol. 2002; 73:322-333. Peri-implant bone loss due to surgical trauma may be associated with bone overheating while preparing the osteotomy site or compression necrosis due to high insertion torque values.

14. Cardemil, C.; Ristevski, Z.; Alsén, B.; Dahlin, C. Influence of Different Operatory Setups on Implant Survival Rate: A Retrospective Clinical Study. Clin. Implant Dent. Relat. Res. 2009, 11, 288–291.
15. Chacon, G.E.; Bower, D.L.; Larsen, P.E.; McGlumphy, E.A.; Beck, F.M. Heat Production by 3 Implant Drill Systems after Repeated Drilling and Sterilization. J. Oral Maxillofac. Surg. 2006, 64, 265–269.
16. Gehrke, S.A.; Neto, H.L.; Mardegan, F.E. Investigation of the effect of movement and irrigation systems on temperature in the conventional drilling of cortical bone. Br. J. Oral Maxillofac. Surg. 2013, 51, 953–957.
17. Gehrke, S.A.; Pazetto, M.K.; de Oliveira, S.; Corbella, S.; Taschieri, S.; Mardegan, F.E.C. Study of temperature variation in cortical bone during osteotomies with trephine drills. Clin. Oral Investig. 2014, 18, 1749–1755.
18. Ercoli, C.; Funkenbusch, P.D.; Lee, H.J.; Moss, M.E.; Graser, G.N. The influence of drill wear on cutting efficiency and heat production during osteotomy preparation for dental implants: A study of drill durability. Int. J. Oral Maxillofac. Implant. 2004, 19, 335–349.
19. Tuijthof, G.; Frühwirt, C.; Kment, C. Influence of tool geometry on drilling performance of cortical and trabecular bone. Med. Eng. Phys. 2013, 35, 1165–1172.
20. Eriksson, A.R.; Albrektsson, T.; Albrektsson, B. Heat caused by drilling cortical bone. Temperature measured in vivo in patients and animals. Acta Orthop. Scand. 1984, 55, 629–631.
21. Yacker, M.J.; Klein, M. The effect of irrigation on osteotomy depth and bur diameter. Int. J. Oral Maxillofac. Implant. 1996, 11, 634–638.
22. Stelzle, F.; Frenkel, C.; Riemann, M.; Knipfer, C.; Stockmann, P.; Nkenke, E. The effect of load on heat production, thermal effects, and expenditure of time during implant site preparation—An experimental ex vivo comparison between piezosurgery and conventional drilling. Clin. Oral Implant. Res. 2014, 25, 140–148.
23. Albrektsson, T.; Albrektsson, B. Microcirculation in grafted bone. A chamber technique for vital microscopy of rabbit bone transplants. Acta Orthop. Scand. 1978, 49, 1–7.
24. Jochum, R.M.; Reichart, P.A. Influence of multiple use of Timedur-titanium cannon drills: Thermal response and scanning electron microscopic findings. Clin. Oral Implant. Res. 2000, 11, 139–144.
25. Strbac, G.D.; Unger, E.; Donner, R.; Bijak, M.; Watzek, G.; Zechner, W. Thermal effects of a combined irrigation method during implant site drilling. A standardized in vitro study using a bovine rib model. Clin. Oral Implant. Res. 2012, 25, 665–674.
26. Soldatos, N., Pham H, Fakhouri, W. et al. Temperature changes during implant osteotomy preparations in human cadaver tibiae comparing MIS® straight drills with Densah® burs. Genes (Basel). 2022 Sep 24; 13 (10): 1716.
27. Bhargava N, Perrotti V, Caponio VCA, et al. Comparison of heat production and bone architecture changes in the implant site preparation with compressive osteotomes, osseodensification technique, piezoelectric devices, and standard drills: an ex vivo study on porcine ribs. Odontology. 2023 111:142-153.
28. Misch, C.; Qu, Z.; Bidez, W. Mechanical properties of trabecular bone in the human mandible: Implications for dental implant treatment planning and surgical placement. J. Oral Maxillofac. Surg. 1999; 57: 700–706.
29. Soldatos N, Nelson-Rabe L, Palanker N. et al. Temperature changes during implant osteotomy preparations in fresh human cadaver tibiae, comparing straight with tapered drills. Materials (Basel). 2022 Mar 23; 15(7): 2369.
30. R Core Team. R: A Language and Environment for Statistical Computing; R Foundation for Statistical Computing: Vienna, Austria, 2021; Available online: https://www.R-project.org/ (accessed in March 2023)

31. Eriksson AR, Adell R. Temperatures during drilling for the placement of implants using the osseointegration technique. J Oral Maxillofac Surg 1986; 44: 4-7.
32. Eriksson AR, Albrektsson T. The effect of heat on bone regeneration: an experimental study in the rabbit using the bone growth chamber. J Oral Maxillofac Surg 1984;42: 705-711.
33. Misic T, Markovic A, Todorovic A, et al. An in vitro study of temperature changes in type 4 bone during implant placement: Bone condensing versus bone drilling. Oral Surg. Oral Med. Oral Pathol. Oral Radiol. Endodontol. 2011, 112, 28–33.
34. Rashad, A.; Kaiser, A.; Prochnow, N.; Schmitz, I.; Hoffmann, E.; Maurer, P. Heat production during different ultrasonic and conventional osteotomy preparations for dental implants. Clin. Oral Implant. Res. 2011, 22, 1361–1365.
35. Bulloch SE, Olsen RG, Bulloch B. Comparison of heat generation between internally guided (cannulated) single drill and traditional sequential drilling with and without a drill guide for dental implants. Int J Oral Maxillofac. Implant. 2012; (27): 1456–1460.
36. Jochum R, Reichart P. Influence of multiple use of Timedur-titanium cannon drills: Thermal response and scanning electron microscopic findings. Clin Oral Implant Res 2000; 11:139-144.
37. Trisi, P.; Berardini, M.; Falco, A.; Vulpiani, M.P. Effect of temperature on the dental implant osseointegration development in low-density bone: An in vivo histological evaluation. Implant Dent. 2015, 24, 96–100.
38. Renders, G.A.P.; Mulder, L.; Van Ruijven, L.J.; Van Eijden, T.M.G.J. Porosity of human mandibular condylar bone. J. Anat. 2007, 210, 239–248.
39. Romeo D, Chochlidakis K, Barmak AB, et al. Insertion and removal torque of dental implants placed using different drilling protocols: An experimental study on artificial bone substitutes. J Prosthodont. 2023; 32: 633–638.
40. Soldatos N, Gozalo D, Moreno D, Powell C. Temperature Changes During Implant Osteotomies Utilizing three different implant systems: A pilot study. JIACD 2016; 8: 34-43.
41. Kold S, Bechtold JE, Ding M, et al. Compacted cancellous bone has a spring-back effect. Acta Orthop Scand 2003; 74: 591–595.
42. Huwais S, Meyer E. A novel osseous densification approach in implant osteotomy preparation to increase biomechanical primary stability, bone mineral density, and bone-to-implant contact. Int J Oral Maxillofac Implants. 2017; 32: 27-36.
43. dos Santos, P.L.; Queiroz, T.P.; Margonar, R.; de Souza Carvalho, A.C.G.; Betoni, W., Jr. Evaluation of bone heating, drill deformation, and drill roughness after implant osteotomy: Guided surgery and classic drilling procedure. Int. J. Oral Maxillofac. Implant. 2014, 29, 51–58.
44. Barrak, I.; Joób-Fancsaly, Á.; Braunitzer, G.; Varga, E., Jr.; Boa, K.; Piffkó, J. Intraosseous heat generation during osteotomy performed freehand and through template with an integrated metal guide sleeve: An in vitro study. Implant Dent. 2018, 27, 342-350.
45. Matthews LS, Hirsch C. Temperatures measured in human cortical bone when drilling. J Bone Jt Surg Am. 1972; 54: 297–308.
46. Benington IC, Biagioni PA, Crossey PJ, et al. Temperature changes in bovine mandibular bone during implant site preparation: An assessment using infra-red thermography. J Dent. 1996; 24: 263–267.
47. Misir AF, Sumer M, Yenisey M, et al. Effect of surgical drill guide on heat generated from implant drilling. J Oral Maxillofac Surg. 2009; 67: 2663–2668.
48. Jochum RM, Reichart PA. Influence of multiple use of timedur titanium cannon drills: Thermal response and scanning electron microscopic findings. Clin Oral Implants Res. 2000; 11: 139–143.
49. Oliveira N, Alaejos-Algarra F, Mareque-Bueno J, et al. Thermal changes and drill wear in bovine bone during implant site preparation. A comparative in vitro study: Twisted stainless steel and ceramic drills. Clin Oral Implants Res. 2012; 23: 963–969.

50. Allsobrook OF, Leichter J, Holborrow D, et al. Descriptive study of the longevity of dental implant surgery drills. Clin Implant Dent Relat Res. 2011; 13: 244–254.
51. Chacon, G.E.; Bower, D.L.; Larsen, P.E.; McGlumphy, E.A.; Beck, F.M. Heat Production by 3 Implant Drill Systems after Repeated Drilling and Sterilization. J. Oral Maxillofac. Surg. 2006, 64, 265–269.
52. Scarano, A.; Piattelli, A.; Assenza, B.; Carinci, F.; Di Donato, L.; Romani, G.L.; Merla, A. Infrared Thermographic Evaluation of Temperature Modifications Induced during Implant Site Preparation with Cylindrical versus Conical Drills. Clin. Implant Dent. Relat. Res. 2009, 13, 319–323.
53. K. Yu, S. Iwata, K. Ohnishi, S. Usuda, T. Nakagawa and H. Kawana, "Modeling and experimentation of drilling vibration for implant cutting force presenting system," *2014 IEEE 13th International Workshop on Advanced Motion Control (AMC), Yokohama*, Japan, 2014, pp. 711-716, doi: 10.1109/AMC.2014.6823368.