In-Vitro Heat Generation During Removal of a Fractured Screw Segment From a Dental Implant

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In-Vitro Heat Generation During Removal of a Fractured Screw Segment From a Dental Implant

This thesis is submitted by Sergio R. Arias and has been examined and approved by an appointed committee of the faculty of the School of Graduate Studies of the Georgia Regents University.

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This thesis/dissertation is therefore in partial fulfillment of the requirements for the degree of Master of Science.

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ABSTRACT

Objective: To compare in-vitro, peak temperature rise during removal of a fractured abutment screw segment from implants placed in a porcine mandible when using two commonly used drilling speeds: 600 or 2,000 RPM.

Material and Methods: Twenty 4.3 x 13 mm implants (Nobel Replace Tapered, Nobel Biocare, Yorba Linda, CA) were placed in ten dissected porcine mandibles (two implants per mandible), one on each side. Localized defects were created in twenty surface-treated abutment screws (Nobel Biocare, Yorba Linda, CA), which were then torqued into each implant until a reproducible fracture occurred in each screw. Three Type-K thermocouples (Omega Engineering, Stamford, CT) were inserted through the buccal bone to contact the implant surface at 3 mm (crestal), 6 mm (mid-body) and 9 mm (apical) depths from the implant platform. The fractured screws were removed utilizing a handpiece removal kit (Broken Screw Extractor Kit, Rhein83, New Rochelle, NY) and room temperature water irrigation using either 600 or 2,000 RPM. Real-time temperature data were obtained at the three locations, and local peak temperature values were recorded. A 2-way ANOVA was performed, using Tukey's post-hoc test at a preset alpha of 0.05.

Results: Mean peak temperatures were significantly higher using 2,000 RPM than at 600 RPM at the mid-body (p < 0.001) and crestal (p = 0.003) regions, but not at the apical (p = 0.225) locations. No statistical differences in mean peak temperatures were found among the three locations using 600 RPM (p = 0.179). In the 2,000 RPM group, mean peak temperature at the mid-body was consistently higher than that at the apical (p < 0.001) area, and more instances of temperature rise above 56° and 60° were observed. In one implant from this group, estimated peak temperature exceeded the bone-damage threshold value (50°C for 30 sec).

Conclusion: Removal of fractured abutment screw segments should be performed using low speed (600 RPM) rather than at 2,000 RPM, to minimize temperature rise in adjacent bone.

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DEDICATION

I dedicate this thesis to my parents Ramon and Pura, who provided me with the encouragement to reach for my dreams and the discipline to make my dreams a reality. To them I owe who I am.

INTRODUCTION

STATEMENT OF THE PROBLEM

Since the early 1980s, oral implants have provided a new dimension to all fields of dentistry. Use of dental implants in the rehabilitation of partially and completely edentulous jaws has become a well-established and accepted contemporary clinical treatment, due to its success and predictability. Implant procedures have developed rapidly and gained an important place in treatment planning. Currently, implant dentistry is an integral part of pre-doctoral curriculum of dental schools in the United States and Canada.

The success rate of dental implants is well documented in the literature, with excellent survival rates after five and ten years of service. However, prosthetic complications do occur during clinical procedures associated with this treatment modality. Mechanical complications include screw loosening, screw fracture, prosthesis fracture, and problems with attachments for overdentures.

In implant dentistry, a screw is used to connect the abutment components to the implant body. A screw also may be used to fix the prosthesis to the abutment or directly to the implant body. In an effort to avoid surgical removal of the bone-integrated dental implant, due to the complication of an irretrievable broken screw fragment, different procedures have been presented. The methods described involve use of rotary instrumentation and/or ultrasonic instrumentation. However, friction created during drill removal of a segmented screw from the

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implant body is expected to create heat from the use of rotary instruments. Excessive heat generation at the implant-bone interface may cause irreversible bone injury and compromise osseointegration. Because of the low thermal conductivity of bone, the heat generated at the implant bone interface during drilling is not dissipated quickly. This heat can lead to local necrosis, which can delay bone repair and affect implant integration.

SIGNIFICANCE

This study will establish the effect of drilling speed when removing a fractured abutment screw segment from an osseointegrated dental implant while minimizing the potential for thermal bone damage. There is no defining treatment protocol for removal of a fractured screw segment from the internal threads of dental implants. Use of a hand piece to drill or create a channel to allow retrieval of the screw is the most common alternative. However, during the drilling process, heat is generated that may reach the implant-bone interface and affect bone viability and may also degrade osseointegration. Currently no in-vitro study has been performed to measure the amount of heat generated at the implant-bone interface during removal of fractured screws.

REVIEW OF THE LITERATURE

DENTAL IMPLANTS

The main objectives of a dental treatment are to restore function, speech, health, and aesthetics. Dental implants are an ideal treatment alternative for rehabilitating patients who are partially or fully edentulous, due to periodontal disease, trauma, or other reasons. Implants (considered an artificial tooth root) are prosthetic devices made of alloplastic material implanted into the oral tissues beneath the mucosal and periosteal layers, and within the bone, to provide retention and support for a fixed or removable dental prosthesis, where natural teeth are missing. Professor Per-Ingvar Brånemark used the term "osseointegration" to describe the process of healing and remodeling of periimplant tissues creating direct bone anchorage to the implant body [1, 2].

Dental implants are a successful treatment modality for rehabilitating partially and fully edentulous jaws. Osseointegration is expected to occur in approximately 97% to 98% of cases [3-5]. Furthermore, the literature reports survival rates, after 5 years of service, ranging between 95% and 97%, and 89% to 94%, after 10 years [6-9].

In a survey of US and Canadian dental schools, 97% of students received didactic instruction in dental implants, and 86% received laboratory and/or clinical experience [10]. At the beginning of this century, there were 25 dental implant manufacturers marketing approximately 100 different dental implant systems,

each having a variety of diameters, lengths, surfaces, platforms, interfaces, and body shapes [11]. In addition, the number of patients requesting implantsupported reconstruction has also increased considerably in recent years [12]. More than 1 million dental implants are inserted annually in North America, with the dental implant market expected to continue to grow strongly at a rate of 10 percent per year, through 2016 [13].

Despite the high survival rate of implants, mechanical complications occur. A large number of complications have been reported [14]. A systematic review of the literature reported up to 19% incidence of implant prosthetic screw fracture and up to 8% fracture of implant abutment screws [15]. Most reports indicate that implant abutment screw fractures are attributed to framework misfit, extended period of clinical use, or repeated retightening of loosened screws [16-18].

When a fractured prosthetic screw becomes trapped within the internal threads of the implant, it is difficult to retrieve. In some situations, it may not be possible to retrieve the screw fragment, and the implant is rendered useless [19]. An unrestorable implant becomes a clinical challenge. For the patient, this condition usually involves increased expense and additional procedures. Different alternatives have been described to deal with a non-restorable implant [20]. One solution is to leave the osseointegrated implant submerged below the soft tissue and to modify the prosthesis design to be supported by other implants. If additional implants prove necessary, they can be placed elsewhere, in accordance with the existing anatomical possibilities [21].

Another treatment option would be to remove the implant. This procedure entails atraumatic removal of the implant with minimal loss of bone, the need to reestablish adequate length and width of the implant site, and lastly, osseointegration of a replacement implant must be achieved before restorative treatment can be initiated [22]. Therefore, the retrieval of a fractured screw fragment is of great important to the clinician.

Various techniques have been presented for retrieving the screw fragment. One method describes the use of a modified no. 1 bur (Brasseler USA, Savannah, GA) with a slow-speed handpiece (500 RPM - 15,000 RPM), in a reversing fashion, to remove a fractured abutment screw. The objective of this procedure is to have the bur blades contact the fractured portion of the screw to produce a reversal of the screw segment, without damaging the internal thread of the implant [23]. Implant manufacturers have also designed dedicated tools for screw segment retrieval. One system involves drilling an access channel through the center of the fractured screw remnant, engaging it, and applying a reverse torque (abutment screw retrieval system, Nobel Biocare, Yorba Linda, CA). Nevertheless, implant abutment/prosthetic screw retrieval remains challenging and time-consuming [24-27].

All the methods preciously described for screw retrieval utilize a rotary drilling process. However, there is lack of specific information from manufactures concerning drilling speed, irrigation method, intermittent drilling motion, and other details (Table 1).

 Table 1. Different screw retrieval systems with manufacturer recommendation for

 speed, irrigation, and rotary instrumentation

Company Screw Retrieval System	Speed	Irrigation	Rotary Instrument
Nobel Biocare®	Not Specified	Copious irrigation with saline solution	Surgical Implant Motor set in reverse rotation
Straumann®	600 RPM	Copious irrigation and lubrication	Surgical Implant Motor set in reverse rotation
Rhein83®	2,000 RPM	Not specified	Surgical Implant Motor set in reverse rotation

When drilling through a titanium prosthetic item, kinetic friction is generated, and this energy transforms to heat [28]. Excessive heat generation at the implantbone interface can cause irreversible bone damage and can compromise osseointegration [29]. Therefore, it is important to know how much heat is generated at the implant/bone interface during the drilling process for retrieval of the titanium-fractured screw segment, so that the screw segment is removed and the biological impact is minimized.

Implant Prosthesis Connection

The implant body (fixture) is that portion of an implant designed to be surgically placed in the bone and may extend slightly above the crest of the residual ridge. The implant body has a crest module, body, and apical region (Figure 1A). The crestal module of an implant body is that portion designed to retain the prosthetic component. An antirotation feature is included on the crest module (external connection) or extends within the implant body (internal connection) to prevent unwanted abutment rotation (Figure 1B) [30]. The abutment is the portion of the implant that supports or retains a prosthesis or implant suprastructure (Figure 2) [31].

The most common implant prosthesis design combines a separate implant body and abutment, providing only implant body placement during bone healing, followed by a second procedure to attach the abutment or prosthesis (Figure 3) [32]. The majority of implant systems require a screw to attach the abutment, framework, or prosthesis to the implant. Cementation of the abutment or prosthesis directly to the implant fixture is no longer a common alternative [33].



Figure 1. A) Implant body sections: crest module, body and apex. B) External

and internal implant abutment connection [34].



Figure 2. Zirconia and metal implant abutments [34]



Figure 3. After implant stabilization, the prosthesis is attached. A) Cementretained restoration: individual abutments are screwed to the implants and the prosthesis is cemented over abutments. B) Screw-retained restoration: prosthesis is attached directly to the implant body with screws [34].

Prosthetic screw

The prosthetic screw is an implant component that secures the implant abutment or prosthesis to the implant body (Figure 4) [30]. This screw is an important component of the implant-supported restoration. Loosening of the screw may result in displacement of the prosthesis and eventual loss of prosthetic function [35]. In implant prosthodontics, applying an appropriate level of tightening torque to the prosthetic screws will create a clamping force (preload) at the abutment and implant interfaces. This force minimizes the potential for abutment/prosthetic screw loosening and subsequent fracture [36]. The recommended tightening torque varies among manufacturers, due to differences in screw designs and the materials used. However, if the screw tightening torque exceeds the ultimate strength of that fastener, screw fracture results [37].



Figure 4. Details of a prosthetic screw design, and a sectional view of the abutment fastened to the implant with a screw [34]

Screw mechanics

Torque is defined as the movement of a system of forces producing rotation [31]. The torque applied to an abutment screw has a clamping effect, called the preload, which holds the abutment to the implant [38]. In external connection designs, the integrity of the implant-abutment joint is mainly dependent on this clamping effect (Figure 1B) [37, 39]. Therefore, it has been considered that, under high occlusal loads, the external hexagon might allow for micro-movements of the abutment, causing instability of the joint, which may then result in abutment screw loosening or even screw fatigue fracture [35, 40, 41].

In contrast, it is claimed that internal implant connection design offers advantages over the external connection: greater tactile sense in judging complete seating of abutments, more efficient rotation resistance, protection of the fastening screw from flexion associated with lateral forces and thereby limiting screw loosening, and a decrease in the required vertical restorative space. To date, the majority of implant systems are made with an internal connection design [42-44].

Torque Wrench System

Accurate delivery of torque to implant prosthetic screws is critical to generate ideal preload in the screw joint and to offer protection against screw loosening [45]. A hand driver (Figure 5A) is not recommended for final screw tightening, because it is difficult to generate more than 20 Ncm of torque, and because

hand-tightening results in inadequate preload to the implant screw joint [46]. Instead, manufactures recommend the use of a calibrated, mechanical torquelimiting device (MTLD) to ensure adequate torque delivery to implant prosthetic screws (Figure 5B) [47].

Calibrated mechanical torque wrenches are considered mandatory, if proper torque application is expected [48]. However, a change in output torque might be expected after continued clinical use or following sterilization [49, 50]. In addition, MTLDs have been shown to be inaccurate by as much as 455% higher than the targeted value, due to component corrosion. Therefore, annual wrench recalibration is recommended [51].



Figure 5. A) Hand driver. B) Calibrated mechanical torque limiting device (torque

wrench) [34].

Screw loosening and fracture

Torque applied to the abutment screw connects the interfaces of the abutment and implant into a unit called the "screw joint." The screw loosens only if forces acting to separate the screw joint are greater than the forces keeping the abutment and implant together [52]. Off-axial occlusal loading to the implant is an example of forces acting to weaken the abutment-implant screw joint (Figure 6).



Figure 6. Occlusal axis of planned restorations as it relates to implant axis. Load forces applied to the occlusal surface of restoration during chewing are away from the implant long axis. These forces translate into separating forces responsible for screw loosening.

Forces attempting to disengage the joined parts are called "joint-separating forces," while clamping forces keep the parts together. Joint-separating forces do not have to be eliminated to prevent screw loosening. The separating-forces must only remain below the threshold of the established clamping force. If the joint does not open when a force is applied, the screw does not loosen (e.g., off

axis occlusal loading). Therefore, the two primary factors involved in keeping implant screws tight are maximizing the clamping force (pre-load) and minimizing joint-separating forces [33].

Most reported implant abutment screw fractures are attributed to framework misfit, extended period of clinical use, repeated retightening of loose screw, poor design of the implant-abutment connection, inadequate tightening, adverse occlusal forces, reduced clamping force and screw joint movement, and metal fatigue after screw loosening [16-18, 26, 53-55]. Additionally, the surface of a new metal screw has microscopic imperfections in the form of high spots, grooves, and irregularities, such that, when initial torque is applied, only the high spots in the system will be in contact. Flattening and wear of these high spots is described as screw settling, and will result in the loss of some of the initial preload [56]. During occlusal function, the vibration and damping effect at the screw joint can result in a loss of screw preload, and hence produce screw loosening. Because of this effect and due to material creep, screws are recommended to be torqued initially, and again after a ten-minute interval, in order to maximize preload at delivery [57].

Screw fracture and screw loosening are closely linked. It is suggested that screw loosening is the first stage of screw fracture [58]. When a screw loosens, surface damage occurs at high stress locations: particularly at the screw head and the first thread locations. Consequently, it is recommend that loose abutment screws

should always be replaced, because a loose screw could have a fatigue history, predisposing it to fracture [38].

Screw materials

Most implant abutment screws are made from gold, titanium, or gold-coated titanium, with the tensile and yield strengths being highest for gold screws [33]. The yield strength of the screw material has a significant effect on preload: 75% of the yield strength of a gold screw and a titanium screw allows a preload of 890 N and 400 N, respectively [46].

Machinability of Titanium

The machinability of titanium is generally considered to be poor, because of the inherent properties of this metal, such as high chemical reactivity, relatively low thermal conductivity, high strength at high temperature, and low modulus of elasticity [59]. Carbide fissure burs have a greater machining efficiency than diamond burs and are recommended for drilling on titanium dental prostheses [60]. These burs are better for end cutting, produce lower heat, have more blade edges per diameter for cutting, and perform better than steel burs. Carbide burs have heads of cemented carbide in which microscopic carbide particles, usually tungsten carbide, are held together in a matrix of cobalt or nickel [61].

Heat generation, pressure, friction, and stress distribution are the main contributors of drill wear. Wear starts at the sharp corners of the cutting edges and is distributed along the cutting edges, ending at the chisel and drill margin [62]. The drill can be considered damaged once the outer corner wear exceeds 75% of the total margin width (Figure 7) [63].



Figure 7. A method to measure outer corner wear from a fixed reference point

[63]

Methods for removal of broken implant screws

A number of methods are described for removal of a fractured screw segment from the internal threads of dental implants [19, 23-25, 27, 64, 65]. The majority of these methods utilize a rotary motor with a carbide bur for retrieval of the fractured screw segment. One system for screw fragment removal includes the following parts: a manual centering device that fits the internal connection of an implant, a deeper centering device, a reverse carbide cutting drill, a claw reamer bur and an extension holder (Figure 8).



Figure 8. Components of a typical commercial screw removal system: A) Manual centering device precisely fits the internal connection of implant. B) Deeper centering device. C) Reverse cutting drill used to drill into the broken screw end without affecting the internal lateral surfaces of the implant. D) Claw reamer used with the extension for bur (E) and manually rotated counterclockwise rotating shaft to remove the broken screw fragment.

BONE QUALITY RELATED TO IMPLANT DENTISTRY

Bone density

Dense or porous cortical bone is found on the outer surfaces of bone and includes the crest of an edentulous ridge. Coarse and fine trabecular bone types are found within the outer shell of cortical bone and occasionally on the crestal surface of an edentulous residual ridge [66]. In combination, these four increasing macroscopic densities constitute four bone categories located in the edentulous areas of the maxilla and mandible [67].

Type I is composed of homogeneous compact bone. Type II has a thick layer of compact bone surrounding a core of dense trabecular bone. Type III has a thin layer of cortical bone surrounding dense trabecular bone of favorable strength. Type IV has a thin layer of cortical bone surrounding a core of low-density trabecular bone (Figure 9).



Figure 9. Different bone qualities: Type I is composed of homogenous compact bone. Type II has a thick layer of cortical bone surrounding dense trabecular bone. Type III has a thin layer of cortical bone surrounded by dense trabecular bone of favorable strength. Type IV has a thin layer of cortical bone surrounding a core of low-density trabecular bone [67].

Bone to implant contact

The bone-implant contact (BIC) percentage is significantly greater in cortical bone than in trabecular bone. Bone density influences the amount of bone in contact with the implant surface [68]; the very dense Type I bone of a resorbed anterior mandible or of the lingual cortical plate of a posterior mandible provides the highest percentage of bone in contact with an endosteal implant and may

approximate more than 85%. Type II bone, after initial healing, usually has 65% to 75% BIC. Type III bone typically has 40% to 50% BIC after initial healing. The sparse trabeculae of the Type IV bone often found in the posterior maxilla offer fewer areas of contact with the body of the implant. With a machined-surface implant this may approximate less than 30% BIC and is most related to the implant design and surface condition.

TEMPERATURE

Human Body Temperature

Normal human body temperature, also known as "normothermia" or "euthermia," varies from individual-to-individual. There is no single number that represents a normal or healthy temperature for all people under all circumstances, using any specific location of measurement [69].

Different parts of the body have different temperatures. Measurements taken directly inside the body cavity are typically slightly higher than those taken using oral measurements, and oral measurements are somewhat higher than those of the skin surface. The commonly accepted, average core body temperature (taken internally) is 37.0 °C (98.6 °F), and the typical oral (under the tongue) measurement is slightly cooler, at $36.8^{\circ} \pm 0.4^{\circ}$ C (98.2° ± 0.7°F) [70, 71].

Thermal properties

An important application of temperature measurement in dentistry is the measurement of heat during osteotomy preparation for dental implants. Numerous studies have been made on the effect of speed and force in the rise of temperature in bone [72, 73]. Heat assessment using direct recording with thermocouple instruments is a common method to record temperature rise [29, 74]. The thermal conductivity and thermal diffusivity are parameters used to predict the transfer of thermal energy through a material [75].

The thermal conductivity (*K*) of a substance is the quantity of heat in calories, or joules, per second passing through a body 1-cm thick with a cross-section of 1 cm² when the temperature difference is 1° C. The units are cal/sec/cm²/(° C/cm) [76]. The conductivity of a material changes slightly as the surrounding temperature is altered, but generally the difference resulting from temperature changes is much less than the difference that exists between different types of materials [77]. Common experience indicates that metals are better heat conductors than nonmetals (table 2). The measurement of thermal conductivity is performed under steady state conditions. However, it is not the steady state condition at 37°C that is concern during osteotomy preparation or during drilling dental implant components, but the conduction of temperature extremes to the oral tissues. Under these conditions thermal diffusivity may be more relevant [78].

Material	k(W/mk)	
Human tissue (organs/ muscles)	0.5	
Human tissue (fat)	0.2	
Human tissue (skin)	0.3	
Blood	0.5	
Bone	0.5-0.6	
Water	0.62	
Air	0.003	
Glass	1.1	
Aluminum	200	
Cooper	400	

Table 2. Thermal conductivities of different materials including human tissue [79]

Thermal diffusivity (k) is defined as the thermal conductivity (K) divided by the product the product of the specific heat capacity (C) times the density (ρ): k=K/(C ρ), where K is the thermal conductivity, C is the temperature-dependent specific heat at constant pressure (heat capacity), and ρ is the temperature-dependent density [80]. Thermal diffusivity is the parameter that characterizes the transient temperature change within a material when the material is exposed to an environmental temperature stimulus [81]. The value of thermal diffusivity of a material controls the time rate of temperature change as heat passes through a material [82].

Bone reaction to thermal injury

The temperature change and its duration of exposure determine the bone tissue response to heat [83]. Most recent studies of thermal bone injury are related to drilling speed during osteotomy preparations for implant placement [29, 84]. A study that used a thermal chamber for intravital microscopy of heated bone placed in rabbit tibia showed that bone tissues become sensitive to heating at 47°C. When the bone was heated to 47°C for 1 minute, fat-cell injury and inconsistent bone injury were observed and endothelial cells of vascular tissue were more resistant to heating than bone and fat cells [85, 86].

The literature indicates that, during implant site drilling, the temperature at the site should be kept below 47°C and that the drilling should last less than 1 minute. This temperature-time limit is used routinely in research studies using direct recording methods with thermocouples [84, 85].

Bone necrosis occurs as a result of the following intracellular changes: protein denaturation, inactivation of enzymes for cell metabolism, alterations in protoplasmic lipids, cell dehydration and membrane rupture, and finally carbonization [87]. Generated heat causes dislocation in the hydroxyapatite mineral lattice structure and microscopic creep of compact bone [88].

Temperatures ranging from 56°C to 70°C are deleterious to bone tissue, because of alkaline phosphatase denaturation [88, 89]. Furthermore, heating to temperatures of 60°C or more results in a permanent cessation of blood flow and obvious bone tissue necrosis, with no signs of repair, over follow-up periods of 100 days or more [85]. Additionally, the threshold for irreversible enzymatic disturbance to cortical bone is reported to be 50°C, applied for only 30 seconds [90]. Thus, the temperature rise at the bone/implant interface should not exceed these values when internal metal-to-metal drilling occurs during removal of a fractured screw segment.

Temperature at cutting surface of the drill

Excessive temperatures can be generated, when the drill is embedded in the workpiece and heat generation is localized within a small area. The resulting temperatures can lead to accelerated tool wear and reduced tool life. During the drilling process, about 90% of the work of plastic deformation and subsequent fragmentation is converted into heat, producing very high temperatures in the deformation zones and the surrounding regions of the interfaces between the chip, tool, and workpiece [91].

The heat partition between the cutting tool and workpiece depends on the thermal properties of both materials. Because titanium has low thermal conductivity (21.9 W/m K) and diffusivity (9.32 $(m^2/s) \times 10^6$), a larger portion (as high as 80%) of heat generated in its drilling will be absorbed by the tool [92].

High cutting temperature is an important reason for the rapid tool wear commonly observed when drilling titanium [93].

Copious water irrigation during the drilling process is recommended to avoid significant temperature increase beyond critical levels at the implant-bone interface [94]. The average turbine water flow ranges between 30 and 50 ml/min [95]. The use of water irrigation at 30 ml/min on the abutment during drilling can increase the cooling capacity of the implant by up to nine-fold [96].

SUMMARY OF CURRENT KNOWLEDGE

A complication is defined in prosthodontics as "a secondary condition that developed during or after implant surgery or prosthesis placement [15]." A large number of mechanical complications have been reported in dentistry, including overdenture loss of retention, resin veneer fracture of fixed partial denture, porcelain veneer fracture of fixed partial denture, resin base fracture, prosthesis screw fracture, abutment screw fractures, and others [97].

Abutment screw fracture is an example of a reported mechanical problem related to implant components. Causes of screw fracture include screw loosening (which may occur as a result of bruxism), an unfavorable superstructure, overloading, or malfunction [98]. A common approach for removing a fractured or damaged abutment screw is the use of a commercial system that includes reverse-action cutting burs [99]. Dental handpieces can generate high levels of thermal energy against cutting substrates [100]. Intraoral recontouring of fixed abutments, shortening of coping screws, or drilling metal surfaces of implant-retained restorations all carry an inherent risk of heat generation and transfer to the bone-implant interface.

The effect of bone overheating at the interface, when drilling surfaces directly connected to osseointegrated implants, may cause bone damage or even bone death and thus may compromise the bone's ability to survive as a differentiated tissue [85]. If bone is heated to 47°C for 1 minute, fat-cell injury and inconsistent bone injury are observed. Greater tissue injury is seen after heating to 53°C for 1 minute [86]. Bone-heating temperatures of 60°C or more result in permanent vascular stasis and irreparable necrosis of the bone tissue [101].

Currently, there is no standardized protocol among manufacturers of implant screw removal kits concerning instructions for drill speed and coolant irrigation. Recommendations of drilling speeds vary from 600 to 2,000 RPM, and some systems do not provide information about use of air and/or water coolant. Furthermore, there is no information indicating the amount of heat generated when removing a screw fragment from the interior of an implant with drilling procedures. It is important to know if the heat generated during drilling is sufficient to reach the bone temperature survival threshold (47°C for 1 minute), which would affect the bone-implant interface and compromise implant osseointegration. If a standard protocol is devised for the safe removal of a fractured screw segment, then clinicians will have a definitive guideline on how to manage this type of complication with optimal clinical success without causing further harm to the patient.

PURPOSE

The purpose of this study is to measure and compare peak bone temperature rise immediately adjacent to three different locations along an implant surface during removal of fractured abutment screws when the devices are placed into dissected pig jaws. A commercial system designed for removal of fractured screws will be utilized at two different drill speeds (600 RPM and 2,000 RPM) with 75ml/min water irrigation at room temperature.

HYPOTHESES

HYPOTHESIS #1

Higher drilling speed will generate greater peak temperature at the implant/bone interface at all three temperature measurement locations along the implant surface

HYPOTHESIS #2

At the higher drilling speed of 2,000 RPM, the observed peak temperature-time profile will exceed the thresholds for bone damage, while the peak temperature-time profile will stay below the thresholds at the lower speed of 600 RPM. As reference, the threshold values for temperature-time intervals beyond which bone damage is likely to occur include 47 degree Celsius for one minute, 50 degrees for 30 seconds, 56 or 60 degrees for any length of time.

HYPOTHESIS #3

The peak temperature rise will be significantly higher at the implant crestal level than at either the middle or apical locations, regardless of drill speed

MATERIALS AND METHODS

OVERVIEW OF ENTIRE PLAN PROJECT

Temperature change along the surface of a titanium implant was measured during removal of a fractured abutment screw from dental implants utilizing a custom-made, broken screw extraction kit (Rhein83, New Rochelle, NY), when using two different drill speeds: 600 RPM (left side), and 2,000 RPM (right side). Ten fresh Ex-vivo pig mandibles were obtained. The inferior border of the mandibles was selected for implant placement. Mucoperiosteal flap surgery was performed to expose the bone in the region of interest in a routine similar to that used for human implant surgery.
Two 4.3 x 13 mm implants (Nobel Replace Tapered, Nobel Biocare, Yorba Linda, CA) were placed in each side of ten mandibles, following manufacture's operating manual, using a maximum of 35 Ncm of torque. Twenty surface-treated titanium alloy abutment screws (TorqTite Item # 29475, Nobel Biocare, Yorba Linda, CA) were torqued into the implant until fracture. In order to create a reproducible screw separation location, an indentation at the shank-thread level of screws was made under magnification, utilizing a laboratory hand piece with a calibrated separating disk (Item #9527, 20 x 0.3 mm, Komet USA, Rock Hill, SC). The screw was torqued into the implant until separation occurred. Three Type-K (Chromel-Alumel, special tolerance wires) thermocouples (Item # TT-K-30, Omega Engineering, Stamford, CT) were placed in contact with the implant surface, at the crestal (c), mid-body (b) and apical (d) locations respectively. A fourth thermocouple was placed in the bone approximately ten millimeters from the implant, to monitor the temperature of bone distant from implant.

The thermocouples were inserted into holes prepared with a 1-mm diameter drill bit (DEWALT Industrial Tool Co, Baltimore, MD) and customized-orientation guide prior implant placement. Perforations were filled with a silver thermal compound paste (Arctic Silver Incorporated, Visalia, CA). Thermocouples were inserted 3 mm (m), 6 mm (b) and 9 mm (d) from the implant platform, extending into the implant osteotomy site, allowing direct contact with implant surface. Therefore, following implant placement, the thermocouples were stable between the bone and the implant. In addition, a segment of thermocouple wire was used to secure the thermocouples against the mandible.

A Cone beam computed tomography (CBCT) image was made to confirm correct position of the thermocouple. Once the thermocouples were placed and sealed with thermal paste, the specimens were immersed in a thermostatically controlled bath filled with water and adjusted to 37°C for 10 minutes to establish a baseline temperature.

Care was taken during the study to ensure that the temperature of each implant location was at 36.8 ± 4 °C (average oral temperature) before drilling. A contraangled hand-piece was used, with different gear ratios, mounted to a surgical motor (Item #Y1412372, NSK surgic XT surgical implant motor, NSK, Hoffman Estates, IL) to control the different drill speed values: left side= 600 RPM (implant on left side of mandibles) and right side= 2,000 RPM (implant on right side of mandibles). The retained fractured screw segments were removed utilizing a commercial device (Broken Screw Extractor Kit, Rhein83, New Rochelle, NY) for removal of broken screws, following the manufacturer recommendations, while also applying copious amounts of irrigation with water (75 ml/min).

The thermocouple outputs were fed into separate channels of a multi-channel temperature data acquisition system (Model TCIC-USB-ENC, Omega Engineering, Stamford, CT). A custom data acquisition program was developed

to allow for simultaneous, real-time temperature display and data recording with respect to duration of treatment at each of the three locations, using a rate of 5 data points per second, at an accuracy of \pm 1.5 °C [102].

Overall main project design presented as a flow chart in Figure 10.



Figure 10. Flow chart illustrating main project design

Pilot Study

Before commencement of the actual test, a pilot study was performed using epoxy resin blocks to determine the following:

- a) If heat is generated during removal of a broken screw at both drill speeds
- b) If temperature rises at the 3 locations along the implant surface
- c) The difference in peak temperature produced by the two drill speeds
- d) If heat generation exceed the thresholds for bone damage

Subsequent to this knowledge, proper modifications were made and applied to the main study. Furthermore, the main study was prepared utilizing an animal osseous model in a similar approach to a clinical scenario.

The external surface of eight 4.3 x 13 mm implants (Nobel Replace Tapered, Nobel Biocare, Yorba Linda, CA) were air-abraded with aluminum oxide (50 microns) particles. Type-K thermocouples (Omega Engineering) were prepared and spot-welded to the external surface of the implants. The location of thermocouples was at the crestal, mid-body, and apical locations for each implant. A fourth individual thermocouple was placed apart from the implant. Implants were then embedded in a slow-setting, epoxy resin block (Buehler epoxy resin, Lake Bluff, IL) and allowed to cure for 24 hours. Eight surface-treated abutment screws (Nobel Biocare) were torqued into the implant until fracture.

In order to create a reproducible screw separation location, an indentation at the shank-thread level of titanium abutment screws was made under magnification, utilizing a laboratory handpiece having a calibrated separating disk (Item #9527, size 20 x 0.3 mm, Komet USA, Rock Hill, SC). The screw was torqued into the implant using a calibrated mechanical torque-limiting device until separation occurred. The epoxy resin block was immersed (1 mm below implant platform level) in a temperature-controlled water bath maintained at 37°C

A contra-angled handpiece was used with different gear ratios mounted to a surgical motor (Item #Y1412372, NSK surgic XT surgical implant motor, NSK, Hoffman Estates, IL) to provide specific drill rotation speeds: Group A= 600 RPM (4 implants), Group B= 2,000 RPM (4 implants). The fractured screws were removed utilizing a commercial broken screw extractor kit (Rhein83 USA, New Rochelle, NY), following manufacture's recommendations.

The thermocouple outputs were fed into separate channels of a multi-channel temperature data acquisition system (model TCIC-USB-ENC, Omega Engineering). A custom data acquisition program was developed to allow for simultaneous, real-time temperature display and data recording with respect to duration of treatment at each of the three locations along the implant surface, using a rate of 5 data points per second, with an accuracy of ± 1.5 °C [102]



Overall pilot study design presented as a flow chart in Figure 11.

Figure 11. Flow chart of pilot study design

DETAILED METHODOLOGY

Detailed method description for pilot study

Implant and epoxy block preparation

Eight 4.3 x 13 mm implants (item # 32217 Nobel Replace Tapered, Nobel Biocare, Yorba Linda, CA) were selected for the pilot study. The implants were air-abraded (sandblasted) with aluminum oxide (50 microns) particles at 30 psi (Figure 12). Three marks were made on the surface of the implant, measured from crest (cervical) at 3 mm, 6 mm and 9 mm (Figure 13). Thermocouple wire was prepared and spot welded to the external implant surface utilizing an orthodontic spot welder at the 4 amperes setting (Item # J00060, Rocky Mountain Orthodontics, Denver, CO) (Figure 14). A five-millimeter diameter perforation was made in a wooden tongue depressor that was used to stabilize the implant. The crestal portion of the implant was secured to the tongue depressor with sticky wax (Kerr Lab Sticky Wax, Kerr, Orange, CA) (Figure 15).



Figure 12. Air abrading surface of implant with 50 micron aluminum oxide

particles



Figure 13. Thermocouple locations were marked on the external implant surface

(at 3 mm crestal, 6 mm mid-body, and 9 mm apical) measured from implant



platform

Figure 14. Thermocouple wire was spot welded to the implant surface according

to locating marks (crestal, mid-body and apical)



Figure 15. A five-millimeter diameter hole was made in a wooden tongue

depressor, and the most coronal portion of the implant was secured to the tongue

depressor with sticky wax

A medicine-measuring cup was used to contain the epoxy resin. Utilizing a 1-mm diameter hand drill, 4 perforations were made in the cup side for thermocouple wire access. The implant was centered and secured to the cup with sticky wax. Care was taken to assure the implant was positioned in the center of cup (Figure 16 and 17).



Figure 16. Inferior view showing implant centered to the cup



Figure 17. Implant and thermocouple secured to medicine cup with sticky wax

Thermocouples were tested for conductivity utilizing an ohmeter (Model 98025, 7 function multimeter, Harbor Freight Tools, Camarillo, CA) (Figure 18). A slow-setting epoxy resin (Buehler epoxy resin, Lake Bluff, IL) was prepared according to manufacture instructions and poured into each medicine cup (Figure 19). Twenty-four hours was allowed for the resin to cure.



Figure 18. Testing thermocouples for continuity before dispensing epoxy resin



Figure 19. Slow-setting epoxy resin dispensed, and allowed to cure setting for

twenty-four hours

Following epoxy resin setting, the tongue blade was removed and the thermocouple outputs were connected to separate channels of a multi-channel temperature data acquisition system (model TCIC-USB-ENC, Omega Engineering) (Figure 20). The acquisition unit was connected to a computer and a custom-made data acquisition program, allowing simultaneous, real-time temperature display and data recording with respect to duration of treatment, at each of the three locations along the implant surface and the epoxy block, using a rate of 5 data points per second, with an accuracy of ± 1.5 °C [102].



Figure 20. Connecting thermocouple outputs to a multichannel temperature data acquisition unit. Arrow shows were the thermocouple would be connected for recording.

Screw Preparation

Eight surface-treated abutment screws (Nobel Biocare, Yorba Linda, CA) were torqued into the implant until fracture. In order to create a reproducible screw separation location, an indentation at the shank-thread level of the screws was made utilizing a laboratory handpiece under magnification with a calibrated separating disk (Item #9527, 20 x 0.3 mm, Komet USA, Rock Hill, SC) (Figure 21). The screw was torqued into the implant until separation occurred (Figure 22).



Figure 21. A calibrated separating disc (A) was used to create an indentation on screw at shank-thread level (B)



Figure 22. View of screw fragment after separation occurred

Screw fragment removal process

The epoxy block was immersed in a temperature-controlled water bath maintained at 37°C (Figure 23). The water temperature was also measured with an analog thermometer placed in the water bath. Additional temperature readings were made that allowed real-time temperature display from the four-thermocouple sites (Figure 24).



Figure 23. Epoxy block with implant placed in a temperature-controlled water

bath at 37°C





A contra-angled hand-piece was used, with variable gear ratios, mounted to a surgical motor (Item #Y1412372, NSK surgic XT surgical implant motor, NSK, Hoffman Estates, IL) used to control drill rotational speeds: Group A= 600 RPM (4 implants - 4 new drills), Group B= 2,000 RPM (4 implants - 4 new drills). The fractured screws were removed utilizing a commercial device for removal of broken screws (Broken Screw Extractor Kit, Rhein83 USA, New Rochelle, NY) (Figure 25). Only the manual centering device and reverse cutting drill (Rhein83), made to fit 4.3 x 13 mm implants (Nobel Replace Tapered), were used in this study (Figure 26).



Figure 25. Rhein83 implant specific broken screw extraction kit system. A)
Manual centering device fits precisely to the internal connection of implant. B)
Deeper centering device for implants placed 7-10 mm subgingivally. C) Reverse cutting drill bit used to drill the broken screw fragment without affecting the internal surface of implant. D) Claw reamer used with the extension for bur (E) manually in a counterclockwise motion to remove the broken screw fragment.



Figure 26. Manual centering device and reverse-cutting drill, custom-made to fit a

4.3 x 13 mm Nobel Replace Tapered implant

The manual centering device was seated in the correct axis to fit precisely with the internal design of the implant, like a guide sleeve (Figure 27A). A petroleum base medium (Kendall Vaseline, Covidien, Mansfield, Massachusetts) was applied to the bur to act as lubricant prior drilling. Before activating the handpiece in a counter-clockwise direction, the bur was positioned in contact with the broken screw, and maintained in firm continuous contact throughout the initial drilling process (Figure 27B). The activated handpiece rotational speed was set for Group A (600 RPM) or Group B (2,000 RPM). The drilling process was performed in an up-and-down motion, with intermittent pressure, to decrease the chance of overheating the implant, under copious water irrigation (75 ml/min) from the surgical motor. The handpiece was paused approximately once-or twice-per-minute to clean the bur, centering device, and internal surface of implant from screw remnants. Drilling was sustained until the reverse cutting bur reached full depth or complete removal of the retained broken screw was achieved (Figure 28). After screw removal, the time for the implant to return to baseline temperature (36.8 ±4 °C) was monitored.



Figure 27. A) Manual centering device seated in the correct axis. B) Reverserotation cutting bur in contact with the coronal broken screw head before activating the handpiece in a counter-clockwise rotation.



Figure 28. Broken screw after removal attached to reverse cutting bur

Intended methodology not accomplished

After completion of the pilot study, the investigation was to use the edentulous region between incisors and first premolar for drilling and implant placement in mandibular porcine specimens (Figure 29). A mucoperiosteal flap surgery was performed to expose the bone in that region, in a manner similar to that used for human implant surgery. Two 4.3 x 13 mm implants (Nobel Replace Tapered, Nobel Biocare, Yorba Linda, CA) were placed in each side of ten mandibles following the manufacturer's operating manual (Figure 30).



Figure 29. Edentulous area between incisors and first premolar selected for

implant placement



Figure 30 Implant placed between incisors and premolar

Three Type-K (Chromel-Alumel) thermocouples (Item # TT-K-30, Omega Engineering, Stamford, CT) were placed 1-mm from the implant surface, at the mesial, buccal, and distal sites respectively. The thermocouples were inserted into 0.9 mm-diameter channels prepared using a #2 endodontic Peeso reamer (Union Broach, York, PA) and custom-orientation guide (Figure 31A). Any voids remaining in the channels were filled with a silver thermal compound paste (Arctic Silver, Arctic Silver Incorporated, Visalia CA). The thermocouples were placed 3-mm, 6-mm and 9-mm below the bone surface and parallel to the implant (Figure 31B). In addition, a length of thermocouple wire was used to secure the thermocouples against the mandible. A radiograph was made using a radiopaque thermoplastic material as a radiographic guide to confirm correct positioning of the thermocouples (Figure 32).



Figure 31. A) Thermocouple site preparation with orientation device. B) Top view

of thermocouple sites.



Figure 32. Radiograph showing prospective location of thermocouples, and

proximity to impacted canine and osseous voids

Once the thermocouples were placed and sealed with thermal paste, the specimen was immersed in a thermostatically controlled water bath and warmed to 37° C for 10 minutes, to re-establish the baseline temperature. Care was taken throughout the study to ensure that the temperature of each implant location was at $36.8 \pm 4 \ ^{\circ}$ C (average oral temperature)[70] prior to performing screw removal procedures.

During the drilling process, however, the drill bits broke before complete removal of the fractured screw segment. The implant angulation made drilling difficult and unstable, resulting in bit fracture.

Problems encountered with this methodology, using the edentulous area between incisors and premolar for the implant site, were:

- 1. Multiple non-erupted teeth, including canines, at the planned surgical site.
- 2. Mandibular incisors with long roots extending in a horizontal direction, limiting space for implant placement.
- 3. The narrow width of the alveolar ridge in the selected area made correct implant placement difficult or impossible.
- 4. Random areas of cancellous bone (type IV), rendered thermocouples and implants unstable.
- 5. Difficult drilling angulations frequently resulted in fracture of drill bits, before complete removal of the broken screw segments.

Detailed description of revised pig jaw methodology

Pig jaw implant site preparation

Ten fresh pig mandibles were obtained from a local meat store (Figure 33A). The inferior border of the mandibles was selected for drilling and implant placement in a manner similar to that used for human implant surgery on vital tissues (Figure 33B). Two Implants were placed in each mandible (total of 20 implants), one on the right and one on the left side.



Figure 33. A) Superior view of pig mandible. B) Inferior view of mandible with revised planned implant sites on right and left sides.

Mucoperiosteal flap surgery was performed to expose the bone in the region of interest. A #15 surgical scalpel blade (Miltex, York, PA 17402), and Molt #9 periosteal elevator instrument (Hu-Friedy Mfg, Chicago, IL 60618) were used, in a manner similar to that used for implant placement for human patients (Figure 34A-B).



Figure 34. A) Incision made with #15 surgical blade. B) Flap elevated with Molt #9 periosteal elevating instrument.

Following manufacturer's operating instructions (Nobel Biocare, Yorba Linda, CA) the osteotomy preparation was made for placement of 4.3 mm diameter x 13 mm long Nobel Replace implant under copious water irrigation. A precision drill was used to penetrate the cortical bone and create a crestal starting point (Figure 35).



Figure 35. Cortical bone penetration with precision drill

A two-millimeter diameter drill with tapered tip was used to penetrate the bone to the desired depth (Figure 36). This step was followed by osseous preparation, with 3.5 and 4.3 mm tapered drills to a final depth of 13 mm (Figure 37).



Figure 36. Initial bone preparation with two-millimeter diameter, tapered tip drill to the desired depth



Figure 37. A) Osteotomy preparation with intermediate 3.5 x 13 mm tapered drill.

B) Implant site preparation finalized with 4.3 x 13 mm tapered drill.

Thermocouple site preparation

The planned position for thermocouple placement was at 3 mm (crestal), 6 mm (mid-body), and 9 mm (apical) locations from the implant platform (Figure 38). A customized orientation device was fabricated utilizing computer-aided design/computer aided manufacturing (CAD/CAM) and 3D printing technology (Figure 39). The orientation device provided consistent bone perforation placement for thermocouples, and was formed into an "L" shape; one side had one perforation that precisely fitted the shank of the 4.3 mm tapered drill, and the other side had three perforations lateral to the implant site that provided consistent guided bone preparation for thermocouple placement in all specimens (Figure 40). Bone channels for the thermocouples were made using a 1 mm diameter drill bit, extending into the implant site (Figure 41).



Figure 38. Planned thermocouple positions at crestal, mid-body, and apical locations. Screw fragment position between crest and body thermocouple locations.



Figure 39. 3D printer used to fabricate orientation device



Figure 40. The orientation device is seen seated on a 4.3 mm tapered drill. Three perforations on the side parallel to the drill allowed thermocouple site preparation



Figure 41. Lateral guided perforations extending into the implant osteotomy

The bone perforations for the thermocouple wires were filled with thermal compound paste (Artic Silver, Arctic Silver Incorporated, Visalia, CA) (Figure 42A). Thermocouple wires were placed in the channels, extending into the lateral implant surface (Figure 42B-C). The implant was inserted into the osteotomy preparation utilizing a hand torque wrench (Figure 43). Therefore, following implant placement, the thermocouples were stabilized between the bone and implant surface. In addition, a length of thermocouple wire was used to secure the thermocouples against the mandible. A cone beam computerized tomography (CBCT) image was made to verify the location of the thermocouples (Figure 44).



Figure 42. A) Thermal compound paste injected into the bone perforations. B) Thermocouple placed in the bone perforations. C) Thermocouples extended into the implant osteotomy to allow direct contact with the implant surface.



Figure 43. Implant placed in direct contact with the three thermocouples. Arrow

shows the wire used to secure the thermocouples.



Figure 44. The CBCT image shows position of thermocouples in contact with the

implant

Screw separation

A pre-weakened abutment screw was torqued into the implant until separation occurred (Figure 45). The estimated position of the screw fragment after separation was between crestal and mid-body locations (Figure 38). The screw was prepared before insertion in the same manner as described in the pilot study (Figure 21A-B). The mandibular specimen was placed in a temperature-controlled water bath. The water level was adjusted to cover the three thermocouples (Figure 46).



Figure 45. Abutment screw was tightened until separation occurred



Figure 46. Prepared specimen placed in a temperature-controlled water bath at

Screw segment removal

Removal of the screw segment was performed in the same fashion as in the pilot study. The manual centering device was seated on the implant platform and into the implant, like a guide sleeve (Figure 47A). A petrolatum medium (Kendall Vaseline, Covidien, Mansfield, Massachusetts) was applied to the bur to act as lubricant prior drilling. With the bur positioned in contact with the broken screw segment, the handpiece was activated in a counterclockwise direction.

The activated handpiece rotational speed was set for the left side group (at 600 RPM) and for the right side group (at 2,000 RPM). Copious water irrigation through the hand-piece at approximately 75 ml/min, was utilized during all drilling. Drilling was performed in an up-and-down direction, with intermittent pressure, to decrease risk of overheating the implant. The handpiece was paused approximately, twice-per-minute, to clean the bur, centering device, and internal surface of the implant of screw debris. Drilling was continued until the reverse cutting bur reached full depth and/or removal of the retained broken screw segment was achieved (Figure 47B).



Figure 47. A) Manual centering device seated in correct axis. B) Broken screw after removal, attached to reverse cutting bur.

STATISTICAL ANALYSES

Peak temperature data obtained from the pig jaws were analyzed using repeated measures analysis of variance (ANOVA) with one grouping factor at two levels (drilling speed: 600 RPM and 2,000 RPM) and one repeated factor at 3 levels (location: crestal, mid-body, apical). The first step in the analysis was to test for a significant interaction between speed and location. If no significant interaction was found, the next step was to test the main effects for each factor; that is, the null hypothesis that there is no significant difference in peak temperature values between speeds, ignoring the effects of location, and the null hypothesis that there is no significant interaction and the null hypothesis that there is no significant difference values among locations, ignoring the effects of speed.

The final step in the main effects analysis was to use the Tukey-Kramer method for repeated measures to perform all pair-wise comparisons of mean peak temperature among the 3 levels of the location factor. If a significant interaction was found between drilling speed and location, a simple-effects analysis was performed; that is, the drilling speeds were compared separately for each location, and the locations were compared separately for each speed. Bonferroni adjustments were made so that the family-wise error rate for the tests of each factor could be controlled at the 0.05 level. The Tukey-Kramer method for repeated measures was used to perform all pair-wise comparisons of mean peak temperature for the location factor, separately for each drilling speed.

In addition to the above analyses, the exact version of Fisher's exact test was used to compare mean peak temperature values between the two drilling speeds, in terms of the frequency with which certain threshold temperature levels were crossed. Descriptive statistics were used to describe the amount of time spent at or above the 47° and 50° temperature thresholds.

For the peak temperature data obtained using the acrylic blocks, the same repeated measures analysis, as described for the pig jaw data, was used to examine the effect of speed, location, and their interaction on mean peak temperature. Unless otherwise specified, two-tailed Student's t-tests, with a significance level of 0.05, were used for all comparisons. Summary statistics are given as mean peak temperature $^{\circ}C \pm S.D.$ All statistical analyses were performed using SAS 9.3 for Windows (SAS Institute Inc., Cary, NC, 2010).

RESULTS

PILOT STUDY RESULTS: ACRYLIC BLOCK DATA

Summary statistics for peak temperature at each location and drilling speed are presented in Table 3. There was no significant interaction between drilling speed and thermocouple location for peak temperature data (p = 0.361), so main effects were analyzed. The main effect for drilling speed was significant (p = 0.019), as was the main effect for thermocouple location (p = 0.030). The Tukey-Kramer method for repeated measures was used to compare peak temperature values at each location with all others, ignoring the drilling speed.

The mean temperature at the implant mid-body (59.1 \pm 10.6 °C) location differed significantly from that in the crestal (54.6 \pm 9.5°C) (p = 0.025). There was no significant difference in peak temperature rise between the apical and crestal (p = 0.160) locations, or between the apical and the mid-body (p = 0.548).

Because of the relatively small sample size in the acrylic block study (n = 4 per group), and because of the exploratory nature of this study, simple effects for drilling speed and implant location were also examined, even though the interaction between drilling speed and location was not statistically significant. In the analysis of simple effects comparing drilling speeds at each location (Table 4), significant differences in mean peak temperature were found between 600

RPM (50.6 \pm 3.3 °C) and 2,000 RPM (67.7 \pm 7.5 °C) in the mid-body (p = 0.042), but not in the crestal (p = 0.180) or the apical (p = 0.104) locations.

In the analysis of simple effects, comparing peak temperature values among implant locations in the 600 RPM group (Table 5), there were no statistically significant differences noted. (p = 0.496). In the analysis of simple effects, comparing peak temperature among implant locations in the 2,000 RPM group (Table 6), there was a statistically significant effect (p = 0.024). Therefore, the Tukey-Kramer method for repeated measures was used to compare peak temperature values among each implant location.

There was no significant difference in mean peak temperature between the apical and the crestal implant locations (p = 0.495), or between the apical and the mid-body (p = 0.729). Comparison of peak temperature rise between the crestal with the mid-body locations almost reached statistical significance (p = 0.065) in the 2,000 RPM group.

Location	600 RPM (n = 4)	2,000 RPM (n = 4)	Both Drilling speeds Combined (n = 8)	Minimum (n = 8)	Maximum (n = 8)
Apical	50.3 ± 4.2	64.7 ± 10.3	57.5 ± 10.6	44.3	74.1
Mid- body	50.6 ± 3.3	67.7 ± 7.5	59.1 ± 10.6*	45.8	74.0
Crestal	48.2 ± 4.4	60.9 ± 9.2	54.6 ± 9.5*	44.2	70.8
Overall Average	49.7 ± 3.8	64.4 ± 8.7	57.1 ± 10.0	44.2	74.1

Table 3. Mean peak temperature (°C \pm 1 S.D.) by location and drilling speed

Acrylic block data

n= number of specimens

*Significantly different (p = 0.025)

Implant Location	600 RPM (n = 4)	2,000 RPM (n = 4)	Tukey-Kramer p-Value for Drilling Speed Comparison
Apical	50.3 ± 4.2	64.7 ± 10.3	0.104
Mid-body	50.6 ± 3.3	67.7 ± 7.5	0.042*
Crestal	48.2 ± 4.4	60.9 ± 9.2	0.180

Table 4. Mean peak temperature (°C \pm 1 S.D.) by location for 600 RPM and

2,000 RPM Acrylic block data

n= number of specimens

*Significantly different
Mean ± S.D. (n = 4)	Minimum	Maximum
50.3 ± 4.2	44.3	53.6
50.6 ± 3.3	45.8	53.0
48.2 ± 4.4	44.2	54.4
	Mean \pm S.D. (n = 4) 50.3 \pm 4.2 50.6 \pm 3.3 48.2 \pm 4.4	Mean \pm S.D. (n = 4)Minimum50.3 \pm 4.244.350.6 \pm 3.345.848.2 \pm 4.444.2

Table 5. Mean peak temperature (°C \pm 1 S.D.) by location the in 600 RPM

Group - Acrylic block data

n= number of specimens

*Peak temperature values were not significantly different among implant locations

Location*	Mean ± S.D. (n = 4)	Minimum	Maximum
Apical	64.7 ± 10.3	50.0	74.1
Mid-body	67.7 ± 7.5	56.8	74.0
Crestal	60.9 ± 9.2	49.3	70.8

Table 6. Mean peak temperature (°C \pm 1 S.D.) by implant location in the 2,000 RPM Group - Acrylic block data

n= number of specimens

*Peak temperature values were not significantly different among implant locations.

CONCLUSION FROM PILOT STUDY

A mean peak temperature rise was recorded with removal of a fractured screw segment from dental implants embedded in epoxy resin at three different locations (crestal, mid-body, and apical). The mean peak temperature generated was higher using a drilling speed of 2,000 RPM compared to 600 RPM. The overall peak temperature rise using the 2,000 RPM speed group was higher than the thresholds for bone damage. A follow-up study was carried out utilizing a similar approach in wet bone (porcine mandible) for the main study.

MAIN STUDY RESULTS: PIG JAW DATA

Summary statistics of mean peak temperature for each implant location and drilling speed are presented in Table 7. There was a significant interaction between drilling speed and implant location for the peak temperature data (p < 0.001), so simple effects were analyzed. In the analysis of simple effects comparing drilling speeds at each location (Table 8), significant differences in mean peak temperature were found between 600 RPM and 2,000 RPM in the mid-body (p < 0.001) and the crestal (p = 0.003) regions, but not at the apical (p = 0.225) area (Figure 48). In the analysis of simple effects comparing peak temperature rise among implant locations in the 600 RPM group (Table 9), there were no statistically significant differences found (p = 0.179).

Location	600 RPM (n = 10)	2,000 RPM (n = 10)	Both Drilling speeds Combined (n = 20)	Minimum (n = 20)	Maximum (n = 20)
Apical Mid-	41.3 ± 2.0 43 9 + 2 8	49.1 ± 10.3 61 1 + 10 1	45.2 ± 8.3 52 5 + 11 4	37.5 39.8	71.6 81.3
body		52.0.1.7.0	47.4 + 0.2	20.0	0.5.0
Overall	41.1 ± 1.5 42.1 ± 2.5	53.0 ± 7.9 54.4 ± 10.5	47.1 ± 8.3 48.3 ± 9.8	38.9	65.8 81.3
Average					

Table 7. Mean peak temperature (°C \pm 1 S.D.) by implant location and drilling

speed - Pig jaw data

n= number of specimens

Location	600 RPM (n = 10) Temp °C	2,000 RPM (n = 10) Temp °C	Tukey-Kramer p-Value for Drilling Speed Comparison
Apical	41.3 ± 2.0	49.1 ± 10.3	0.225
Mid-body	43.9 ± 2.8	61.1 ± 10.1	< 0.001*
Crestal	41.1 ± 1.5	53.0 ± 7.9	0.003*

Table 8. Mean peak temperature (°C \pm 1 S.D.) by implant location between 600

RPM vs. 2,000 RPM Groups - Pig jaw data

n= number of specimens

*Significantly different



Figure 48. Mean peak temperature comparison between the two selected drilling speeds at the three specified implant locations with respect to drill speed.
Significant differences (*) were found between peak temperature values when using the 600 RPM and 2,000 RPM speeds at the mid-body and crestal locations, but not in the apical area. The vertical bar indicates one standard deviation. N = 10 specimen per group.

Mean ± S.D. (n = 10) Temp °C	Minimum	Maximum
41.3 ± 2.0	37.5	45.1
43.9 ± 2.8	39.8	47.2
41.1 ± 1.5	38.9	43.8
	Mean ± S.D. (n = 10) Temp °C 41.3 ± 2.0 43.9 ± 2.8 41.1 ± 1.5	Mean \pm S.D. (n = 10) Temp °CMinimum41.3 \pm 2.037.543.9 \pm 2.839.841.1 \pm 1.538.9

Table 9. Mean peak temperature (°C \pm 1 S.D.) by implant location in 600 RPM

Group - Pig jaw data

n= number of specimens

*Peak temperature values were not significantly different among implant locations

In the analysis of simple effects comparing peak temperature rise values among implant locations within the 2,000 RPM group (Table 10), there was a statistically significant effect (p < 0.001). Therefore, the Tukey-Kramer method for repeated measures was used to compare peak temperature rise values for each implant location among all others. The mean peak temperature in the mid-body (61.1 ± 10.1 °C) differed significantly from that in the apical (49.1 ± 10.3 °C) (p < 0.001) in the 2,000 RPM group. There was no significant difference in peak temperature rise between the crestal and apical (p = 0.747) locations, or between the crestal and the mid-body (p = 0.126).

Location	Mean ± S.D. (n = 10) Temp °C*	Minimum	Maximum
Apical	49.1 ± 10.3 ^a	41.0	71.6
Mid-body	61.1 ± 10.1 ^b	49.8	81.3
Crestal	$53.0 \pm 7.9^{a,b}$	40.5	65.8

Table 10. Mean peak temperature (°C \pm 1 S.D.) by implant location in the 2,000

RPM Group -	Pig	jaw	data
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n= number of specimens

*Peak temperature values of locations denoted by similar lower case letters as

not significantly different

With regard to the comparisons of the peak temperature rise values between the two drilling speeds, in terms of the frequency with which certain threshold temperature-time levels were crossed, no implants in the 600 RPM group exceeded any of the temperature thresholds (Table 11). In the 2000 RPM group, the 47° for 1 min threshold was not crossed for any implants, and the 50° for 30 sec threshold was crossed for only one implant in the 2,000 RPM group. However, there were significant differences between the 600 RPM and 2,000 RPM groups in terms of the number of times the 56° and 60° thresholds were transgressed (Table 12)(Figure 49). Table 12 contains summary statistics for the amount of time spent at or above the 47° and 50° temperature thresholds.

Temperature- Time Threshold (°C)	600 RPM (n = 30)	2,000 RPM (n = 30)	Fisher-Exact p-Value for Drilling Speed Comparison
47°	0 (0%)	0 (0%)	1.000
50°	0 (0%)	1 (3%)	1.000
56°	0 (0%)	13 (43%)	< 0.001
60°	0 (0%)	10 (33%)	< 0.001

Table 11. Number (percent) of specimens exceeding specific temperature-time

threshold values with respect to drilling speed



Figure 49. Comparison between drilling speeds in terms of frequency with which certain threshold temperature-time levels were exceeded. In the 600 RPM group, no implants crossed any of the temperature thresholds. However, in the 2,000 RPM group, threshold temperatures of 50° (1 time), 56° (13 times) and 60 °C (10 times) was crossed. There were significant differences (*) between the 600 RPM and 2,000 RPM groups in terms of the number of times the 56 and 60 °

thresholds were crossed.

Threshold Temp °C	Time Limit	Speed RPM	Number of Implants Exceeding Threshold	Time Exceeding Threshold (sec) [#]	Minimum	Maximum
47 [°]	1 min	600	1	0.8	0.8	0.8
47 [°]	1 min	2000	21	21.7 ± 11.5	2.6	41.0
50°	30 sec	600	0			
50°	30 sec	2000	18	16.6 ± 9.3	2.6	33.2

Table 12. Mean (± S.D.) Number of Seconds Exceeding Temperature Thresholds

DISCUSSION

The present study analyzed the peak temperature rise along the surface of twenty dental implants measured at three different locations following removal of a titanium alloy abutment screw fragment using a commercial, implant-specific, broken screw retrieval kit (Figure 25). The implants were placed in ten dissected porcine mandibles. The most common implant-related, heat-generating procedure that has been studied is the osteotomy preparation [29, 72, 103-105]. Studies evaluating factors that influence bone temperature during osteotomy preparation have mainly focused on drilling depth [84], drilling speed, drilling time [73], sharpness of the drill [106], pressure applied to the drill [83], and irrigation [107, 108]. Some studies have measured temperature change at the implant surface during prosthetic abutment preparation with a rotary motor [109, 110]. To date, temperature variation at the implant/bone interface when removing a fractured screw segment with rotary instrumentation has not been investigated.

The first hypothesis stated that higher drilling speed would generate greater peak temperature values at the implant/bone interface at all three implant locations than use of the lower speed. The test results showed that mean peak temperatures were significantly higher using 2,000 RPM than with use of 600 RPM in the mid-body (p < 0.001) and crestal (p = 0.003) locations (Figure 48). However, no significant difference was found at the apical location (p = 0.225). Consequently, this hypothesis was partially rejected. The overall mean peak temperature when using 2,000 RPM was 54.4 ± 10.5 °C, compared to 42.1 ± 2.5

when using 600 RPM (Table 7), suggesting an overall disadvantageous temperature environment for bone immediately surrounding the implant.

The second hypothesis stated that: A. at the higher drilling speed of 2,000 RPM, temperature-time profile will exceed the threshold value know to be associated with bone damage, and B, the temperature-time profile will stay below the threshold values at the lower speed of 600 rpm. The threshold values for temperature-time profiles beyond which bone damage is likely to occur include 47 degree Celsius for one minute [85], 50 degrees for 30 seconds [90], and 56 or 60 degrees, for any length of time [85, 88, 89]. The results showed that no implants in the 600 RPM group exceeded any of the above-mentioned temperature-time thresholds. There was no significant difference in the number of incidences found between the 47° and 50° C (p = 1.000) thresholds. However, there was a significant difference between the 600 RPM and 2,000 RPM groups in terms of the number of times the 56° and 60° thresholds were crossed (P <0.001) (Figure 49). In the 2,000 RPM group, the 47° for 1 min threshold was not crossed, and only one implant crossed the 50° for 30 sec threshold (Table11). Therefore, the second hypothesis was partially rejected.

The third hypothesis stated that the peak temperature rise will be highest at the crestal level of the implant, and not at the middle or apical locations, regardless of the speed of the drill. For the 600 RPM group, there was no statistically significant difference (p = 0.179) among the three locations (Table 9). The mean

temperature in the implant mid-body for the 2,000 RPM group differed significantly from that in the apical (p < 0.001) location. However, there was no significant difference between peak temperature at the crestal and the apical (p = 0.747) locations, or between the crestal and the mid-body (p = 0.126) locations (Table 10). Consequently, this hypothesis was rejected.

Drills are often subjected to excessive temperatures, because the bur is embedded in the workpiece, and heat generation is localized in a small area [111]. Furthermore, titanium is classified as a difficult material to cut [112, 113]. The poor machinability of titanium is principally attributed to the following characteristics: 1) its low thermal diffusivity does not allow the heat generated during machining to dissipate, increasing the cutting temperatures, and results in excessive tool deformation and wear [91, 93], 2) its high chemical reactivity at elevated temperatures causes debris to weld to the bur, leading to cratering and premature tool failure [114, 115], 3) its high strength at elevated temperatures does not allow heat generated during machining to dissipate from the tool edge, producing high tool tip temperatures and excessive plastic deformation wear necessitating the use of a greater tool pressure for adequate cutting [116].

The use of water irrigation not only provides cooling but also lubrication, reducing the tool temperature and lessening cutting forces and chip-welding that are commonly experienced with titanium alloys [93]. In a study that evaluated the effect of water irrigation on heat dissipation during abutment preparation of 1piece dental implants, it was reported that water irrigation (30 mL/min) increased the cooling capacity by nine-fold, compared to passive cooling without water [96]. A similar study, investigated the amount of heat generated within the implant mid-body at three locations (mid-body, crestal, and apical) during routine clinical abutment preparation of 1-piece implants. It was reported that abutment preparation with high-speed burs significantly increases the implant surface temperature, when preparations were conducted in ambient air vs. water irrigation.

Furthermore, this work indicated that the highest temperature values were concentrated in the crestal, followed by middle, and apical implant locations [109]. Another study investigated the influence of coolant on machinability of titanium alloy. The results indicated that tool life improved by 30%, when machining with coolant [117]. In the present study, continuous external water irrigation (75ml/min) was used during drilling. However, the water was directed to the centering device, instead of on the reverse-cutting drill (Figure 26, Figure 47A). Also, because of the tight fit between the bur and the centering device, it is likely that only limited amounts of water actually reached the bur tip and screw fragment during drilling. Consequently, this limitation may have reduced the cooling effect of water irrigation expected with this system.

Titanium is highly chemically reactive, with the tendency of welding onto the cutting tool during machining. This adhered material is a main contributor to tool

failure and increased temperature [118]. In the present study, a significant amount of debris was generated during drilling. Furthermore, the tight fit between the bur and the centering device prevented debris from backing out from the workpiece. Therefore, the handpiece was paused approximately twice-perminute to clean the bur, centering device, and internal surfaces of the implant of screw debris, that may allow a decrease in mean peak temperature.

The effects of drilling speed when machining titanium alloy indicates that cutting speed has a significant effect on drill wear [119]. Others report extreme tool wear at high cutting speeds, but wear was dramatically reduced as the speed decreased [93, 120]. Consequently, as the bur wears, cutting effectiveness decreases, generating higher temperature at the drilling site.

The cutting speed also contributes to variation in temperature during drilling of titanium alloys, and temperature increases with higher cutting speed. This knowledge corresponds with the high cutting energy and deformation strain rate of titanium, as well as heat flux increase [121]. Therefore, a greater temperature may be expected when drilling at higher burs speed, due to faster wear of the bur. This finding is consistent with the present study, in which the mean peak temperatures were significantly greater using 2000 RPM than with 600 at the mid-body (p < 0.001) and crestal (p = 0.003) locations, but not the apical portion (p = 0.225).

In the current study, the mean peak temperature for the 2,000 RPM group midbody (61.1°C \pm 10.1) location was higher than that of the crestal (53.0°C \pm 7.9) and apical (49.1°C \pm 10.3) regions. This finding was consistent with the 600 RPM group, were the mean peak temperature at the mid-body (43.9 \pm 2.8) location was higher than that of the crestal (41.1 \pm 1.5) and apical (41.3 \pm 2.0) locations (Table 7). The higher temperature at the mid-body location could be a result of the drilling location and direction water irrigation (Figure 38).

The fractured screw fragment was positioned between the crestal and mid-body thermocouple locations, slightly distant from the apical region (Figure 38). In addition, water irrigation during drilling was directed mainly towards the centering device at the implant crestal, which may decrease the temperature at the crestal location, but not enough to affect the mid-body or apical locations.

The critical temperature-time profiles beyond which bone damage is likely to occur include 47 degree Celsius for one minute, 50 degrees for 30 seconds, and \geq 56 degrees for any length of time [85, 101, 122, 123]. In this study, no implants subjected to drilling speed of 600 RPM exceeded any of the threshold temperature levels. When using 2,000 RPM, no implants were greater than the 47°C for one minute threshold. However, one implant crossed the 50° for 30 sec threshold, thirteen implants crossed the 56°C limit, and ten implants crossed the 60°C value. These results clearly indicate that peak temperature approaching

that of the bone threshold is more likely to occur using a drilling speed of 2,000 RPM than one at 600 RPM.

CONCLUSIONS

Within the limits of the present study, the following conclusions are allowed to be made:

- Removal of a fractured abutment screw segment using a drill speed of 2,000 RPM generates significantly higher mean peak temperature rise than when using 600 RPM, at the mid-body and crestal implant location but not at the apical area.
- Regarding local temperature rise, the drilling speed of 600 RPM does not generate enough heat to exceed the temperature-time thresholds for causing potential bone damage.
- In the 2,000 RPM drill speed group, however, all temperature-time thresholds for bone damage were exceeded, except for the 47°C for one minute limit.
- 4. Unlike the drilling speed of 600 RPM group, the 2,000 RPM speed showed a significant difference in the mean peak temperature in the implant midbody (61.1 ± 10.1 °C) location from that in the apical (53.0 ± 7.9 °C) region.

5. Thus, removal of fractured abutment screw segments should be performed using low speed 600 RPM rather than at 2,000 RPM, to minimize temperature rise in adjacent bone.

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