Transient Heat Transfer in Dental Implants for Thermal Necrosis-Aided Implant Removal: A 3D Finite Element Analysis

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Removal of osseointegrated but otherwise failed (mechanical failure, mispositioning, esthetics, etc) dental implants is a traumatic process resulting in loss of healthy bone and complicating the treatment process. The traumatic effects of implant removal can be reduced by weakening the implant-bone attachment. Thermal necrosis-aided implant removal has been proposed as a minimally invasive method toward this end. In this method, an electrocautery tip is contacted to the implant to increase the temperature to 47°C and generate a limited and controlled thermal necrosis at the bone-implant interface. So far, no controlled studies have been performed to investigate the optimal clinical parameters for this method. In this study, we aimed to investigate, using finite element analysis method, the optimal settings to achieve intentional thermal necrosis on 3 implant systems, at 5 W and 40 W device power and with different size tips. The temperature increase of the implants at 40 W power was very sudden ($<$ 0.5 seconds) and as the bone reached 47°C, the implants were at unacceptable temperatures. At 5 W power, temperature increase of the implants happened at manageable durations ($<$ 1 second). Moreover, the temperature increase was even slower with larger implants and larger tip sizes. Therefore, low power settings must be used for thermal necrosis-aided implant removal. Also, the size of the implant and the tip must be taken into consideration in deciding the duration of contact with the electrocautery tip and the implant.

Key Words: dental implant, implant removal, thermal necrosis, finite element analysis

INTRODUCTION

Implant failure can be mainly divided into 2 categories as early failure and late failure. Early failure occurs during the healing period and has been related to poor osseointegration.[1,2] Therefore, this type of failure is essentially of physiological nature and may result from surgical trauma, infection, and micromovements of the implant during bone remodeling.

The late failure occurs following the occlusal loading of the implant and may result from either biological (peri-implantitis, bacterial plaque subsidence, etc) or mechanical (screw loosening, abutment/screw fracture, implant fracture, implant misplacement, etc) causes.[2–4] For the treatment of late failures of biological origin, nonsurgical or surgical debridement and local antimicrobial therapies have been suggested.[5,6] However, for implants with pain on function, mobility, radiographic bone loss of more than one-half the length of the implant body, and uncontrolled exudate, the suggested mode of treatment is the removal of the implant.[7] In late failures of biological origin, osseointegration process is also compromised since inflammation free healing is essential for osseointegration. On the other hand, in failures of mechanical origin, although considered rare, the severity and the resulting trauma of implant removal is increased due to the osseointegrated nature of the implants.[4] Drills, trephines, bone chisels, piezo-surgery, or fixture removal kits (reverse high torque) are commonly used to achieve this.[8] Although reverse high torque technique has been shown to be effective for removal of osseointegration-compromised implants with minimal bone damage, the research on removal of osseointegrated implants using this technique is very limited.

During the removal of osseointegrated implants, besides the supporting bone, other tissues surrounding the implant, such as, nerves, sinuses, palatine bone, and neighboring teeth can be damaged. For a new implant to be placed, the cavity, where the implant used to be, usually requires augmentation with bone grafts and a recovery period of 9 to 12 months. But sometimes the damages are just irreversible and treatment options other than implants, such as dentures, are considered. Consequently, the intended treatment is delayed, the quality of life of the patients is significantly reduced, and the workload of the surgeon and the cost of the treatment is multiplied.[9,10]

The loss of healthy tissues and the trauma caused by the removal of osseointegrated implants can be reduced by somehow weakening the implant-bone attachment before removal, therefore reducing the force required to remove the

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implant. It has been proposed that this can be achieved by generating a limited and controlled thermal necrosis at the bone-implant interface. In a case report, Cunliffe et al[10] has contacted a unipolar electrosurgery unit to the internal surface of the neck of the implant to remove a mispositioned and unrestorable implant. After 1 week, the implant was removed with a force below 30 N, with no apparent bone loss or macroscopic bone necrosis.[10] Similarly, Massei et al[11] has applied a similar technique by contacting surgical wire on 20 implants to be removed. All the implants were removed with a force lower than 30 Ncm and histological analysis has shown that the thermal necrosis was limited to 50 micrometers.[11] In another case report by Worni et al,[12] laser-induced thermonecrosis was used to remove a mispositioned osseointegrated implant. The implant's inner connection has been heated using a CO_2 laser and 1 week later, the implant has been removed with a force slightly more than 35 Ncm. No complications or further bone loss was observed during the healing period. Although these studies have shown the promise of this method, no controlled and systematic studies have been performed to investigate the full potential and limitations of this method.

A study investigating the use of electrocautery and laser tools in the presence of dental implants has shown that bipolar electrocautery tools can cause up to 5°C increase in temperature at the bone upon contact with dental implants, while unipolar tools can cause temperature increase exceeding 10°C.[13] However, parameters such as the relationship between the contact duration, device power, implant size and the temperature increase, the effect of the temperature increase at the bone and optimal conditions to use thermal necrosis for easier implant removal remains to be investigated.

It is generally accepted that the bone tissue is sensitive to temperatures over 47°C.[14] At 47°C, local and nonprogressive thermal osteonecrosis occur. At 56°C, alkaline phosphatase becomes denatured. At 60°C and above, wide spread and progressive osteonecrosis occur.[14] Therefore, heating the bone-implant interface to 47°C under controlled conditions to weaken the implant-bone attachment by creating a local and limited thermal osteonecrosis can be beneficial in reducing the traumatic results of implant removal.

In this study we aimed to investigate the optimal device power and contact duration to achieve intentional thermal necrosis on 3 implant systems with different geometries using finite element analysis (FEA) method. We have constructed finite element models of 3 different implants in mandible. 5W and 40W power was applied on the implants, simulating contact with unipolar electrocautery tips at low and high output settings and small and large tip sizes. Temperature increase was plotted and the timepoints at which the bone-implant interface reached to 47°C were marked.

Materials and Methods

Model generation

The 3D geometry of the mandibular bone was obtained using computerized tomographic scan data. The data was transferred to 3D-Doctor software (Able Software Corporation, Lexington, Mass) and the bone tissue was isolated based on Hounsfield units. To generate the 3D finite element model of the mandible, the data was imported to the Rhinoceros 4.0 software (McNeel, Seattle, Wash). The generated model, which was a section of edentulous, posterior mandible type II bone according to Lekholm and Zarb classification,[15] consisted of a layer approximately 2 mm of cortical bone surrounding a core of dense trabecular bone. The cortical and trabecular bones were assumed to be perfectly united. The numbers of elements and nodes in the models are shown in Table 1.

Three finite element models were constructed with three different implant systems. The implant systems modeled in the study were Osseospeed Astra Tech (Astra Tech Dental AB, Mölndal, Sweden), MIS (MIS Implants Technologies Ltd, Bar-Lev Industrial Zone, Israel) and Straumann (Straumann, Basel, Switzerland) (Figure 1). The physical properties used in the present study are shown in Table 2.

Finite element analyses

The implants and bones were assumed to be at a uniform 36°C at the beginning of the simulation. To model the effect of the sudden temperature increase in the implant, 5 W and 40 W power was applied on the implant systems with 2 different contact areas simulating touching a unipolar electrosurgery tip with 2 different tip sizes (1.80 mm, and 2.50 mm) (Figure 2) and the temperature increase was calculated. The implant-abutment screw was assumed to be made of the same titanium alloy (Ti6Al4V) as the implants.

The transient heat distribution on the implant, cortical bone, and trabecular bone was investigated. A time step of 0.02 seconds was used. Twelve analyses were performed on 3 different implants (Straumann, MIS, and Astra Tech), 2 different tip sizes (1.80 mm and 2.50 mm), and 2 different power settings (5 W and 40 W). Straumann was chosen to represent a small-sized, crest level implant while MIS represents a mid-sized, bone level implant and the Astra Tech represents a large, bone level implant.

The analyses were performed for a total duration of 4 seconds. The duration for the implant, the cortical bone and the trabecular bone to reach 47°C were calculated for each implant system, tip size, and power output.

Results

The effects of implant geometry, tip size, and power output in heating the implant-bone interface to a desired temperature were evaluated. In this analysis, the durations at which the implants and the trabecular bone were heated to 47°C were almost identical for all calculations. This is due the larger surface of contact between the implant and the trabecular bone compared to the contact area between the implant and the cortical bone. Therefore, the temperature change in trabecular bone was not discussed here, and the term "bone" refers to the cortical bone. The temperature changes in the implant and the cortical bone for all the calculated conditions are shown in Table 3.

At 40 W power, all the implant surfaces reached to 47°C under 1 second. The implant surfaces reached 47°C at 0.16 to 0.26 seconds for 1.80 mm tip size and 0.36 to 0.54 seconds for 2.50 mm tip size. The cortical bone reached to 47°C at 0.80 to

Table 1

Number of nodes and elements and the dimensions of the implant systems

Implant	Straumann	MIS	Osseospeed Astra Tech
Nodes	10 738	23 969	14 153
Elements	50 676	128 704	70 126
Diameter (mm)	4.10	3.75	4.00
Length (mm)	6.00	11.50	13.00

Table 2

Physical properties used in the study

	Implants	Cortical Bone	Trabecular Bone
Density (g/cm^3)	4.38	1.30	1.30
Thermal conductivity (W/[m°K])	6.52	0.59	0.59
Specific heat (kJ/kgK)	0.57	0.44	0.44

1.84 seconds for 1.80 mm contact area and 2.54 to 3.25 seconds for 2.50 mm contact area (Table 3, Figure 3).

At 5 W power, the implant surfaces reached to 47°C at 0.66 to 1.90 seconds for 1.80 mm tip size and 1.20 to 2.50 seconds for 2.50 mm tip size. The cortical bone reached to 47°C at 2.52 to >4.00 seconds for 1.80 mm tip size. For 2.50 mm tip size at 5 W, the cortical bone did not reach to 47°C at 4 seconds, which was the end time of the calculation (Table 3, Figure 4).

At 40 W power, all the implants reached unacceptable temperatures when the cortical bone reached 47°C (Figure 5). Only at 5 W power and 2.50 mm contact area, Astra Tech and MIS implants were at acceptable temperatures (43.68°C and 49.50°C, respectively) at the end of the simulation. The Straumann implant was at 132°C at these conditions when the bone reached to 47°C (Figure 5).

Discussion

In this study, we have investigated the temperature increase resulting from contact with electrocautery tips in 3 different

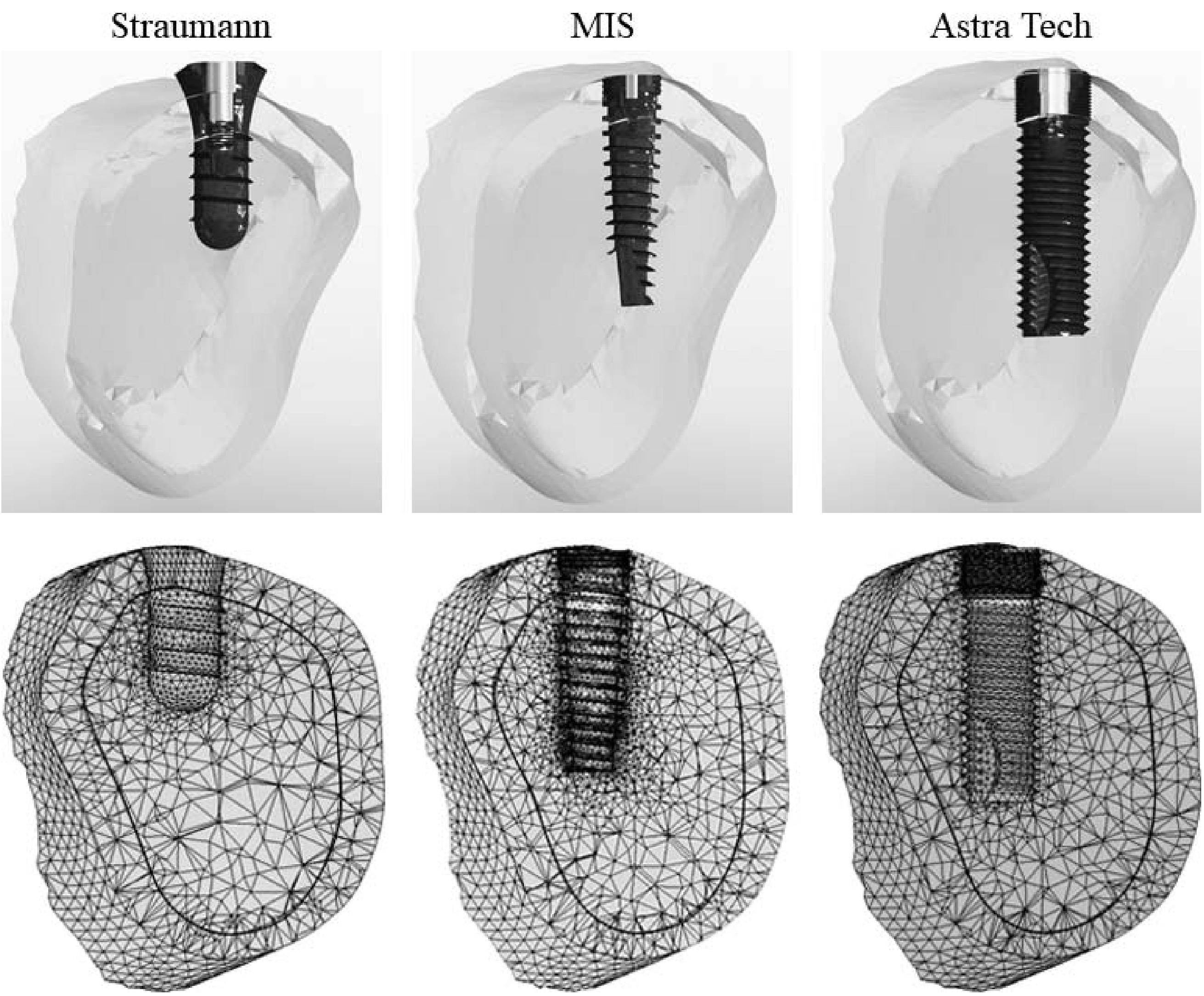


Figure 1. 3D renders and the distribution of elements and nodes with different implant systems.

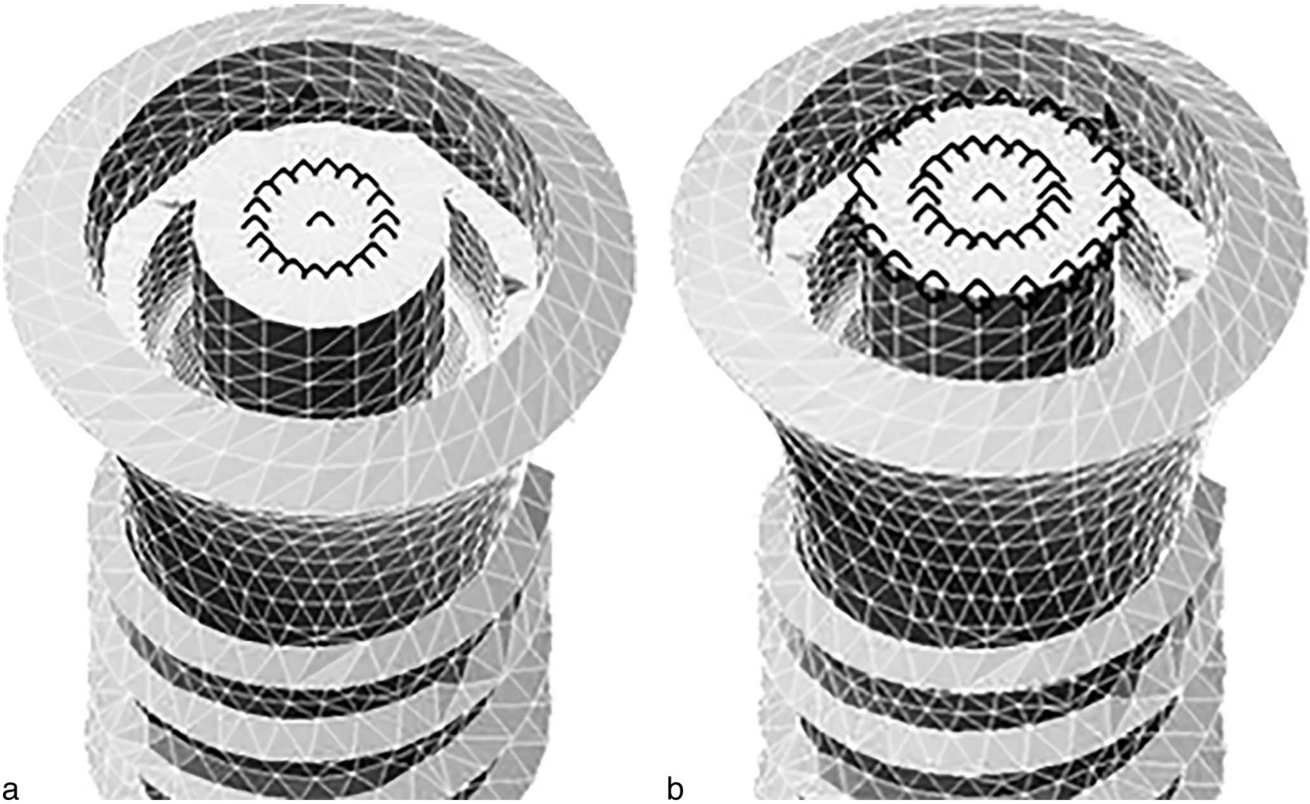


Figure 2. The different contact areas at which the heat was applied: (a) 1.80 mm, (b) 2.50 mm.

implant systems with different geometries using FEA. FEA has been widely used to design and investigate the biomechanical properties of dental implant systems. Since dental implants are more continuous and isotropic materials compared to the tooth, it is relatively easier to make accurate predictions, interpret results, and use in actual clinical cases. Nevertheless, there are some limitations of FEA that must be considered, and the results should be carefully interpreted. The cortical bone of the jaw is anisotropic and nonhomogeneous; however, in this study, all constructed models were assumed to be homogenous, isotropic, and linearly elastic. Besides, 100% osseointegration (bone-implant contact) was assumed, which does not entirely represent the cases in clinical practice. Therefore, temperature increase is expected to be slightly slower in experimental conditions, where the bone to implant contact is not 100%.

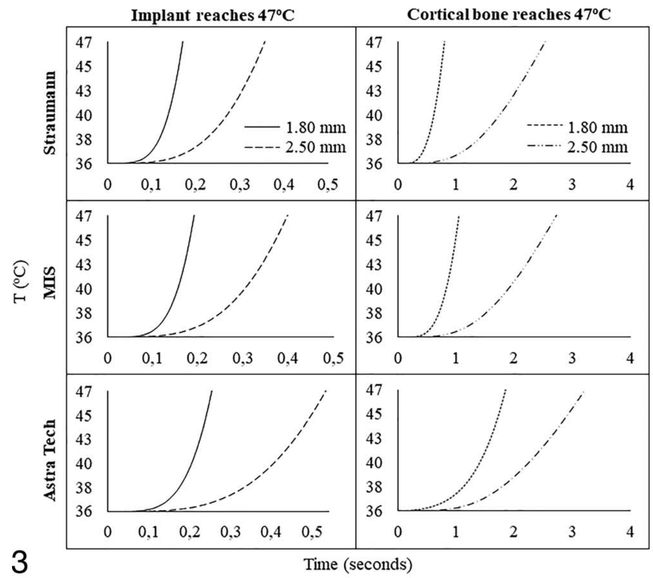
Temperature increase in dental implants has mostly been regarded as an "accidental" or "unwanted" consequence of exposure to hot liquids,[16,17] prosthetic preparation,[18] laser irradiation,[19,20] or contact with electrocautery units.[13] However, in the current study, the conditions for intentional and controlled temperature increase were examined as a technique to facilitate easier removal of implants that are osseointegrated but failed otherwise. The temperature increase is proposed to cause a very limited osteonecrosis at the implant-bone interface.[10,11] Our aim was to lay a groundwork for future systematic studies exploring the potential and limitations of thermal necrosis-aided implant removal. Animal implant models investigating the stability of osseointegrated implants starting from heat application to implant removal and investigating the extent of osteonecrosis at different power settings and different application times via histomorphometric measurements would be crucial for establishing the safety parameters of future clinical studies.

It has been reported in a technical report[11] and 2 case reports[10,12] that failed dental implants has been removed by applying smaller torque when the implant is heated by contacting electrocautery tips or applying laser to the implant. However, these reports have focused mainly on the removal torque of the implants and subsequent clinical parameters, such as complications with healing or further bone loss. The temperature increase in the implants or the bone was not

Table 3

Duration (seconds) at which the implant and the cortical bone reached 47°C for different implant systems, contact areas, and device powers

Device Power, W	Tip Size, mm	Location	System: Straumann	System: MIS	System: Astra Tech
40	1.80	Implant	0.16	0.2	0.26
		Bone	0.8	1.06	1.84
	2.50	Implant	0.36	0.4	0.54
		Bone	2.54	2.76	3.25
5	1.80	Implant	0.66	1.2	1.9
		Bone	2.52	3.8	> 4.00
	2.50	Implant	1.2	1.52	2.5
		Bone	> 4.00	>> 4.00	>> 4.00



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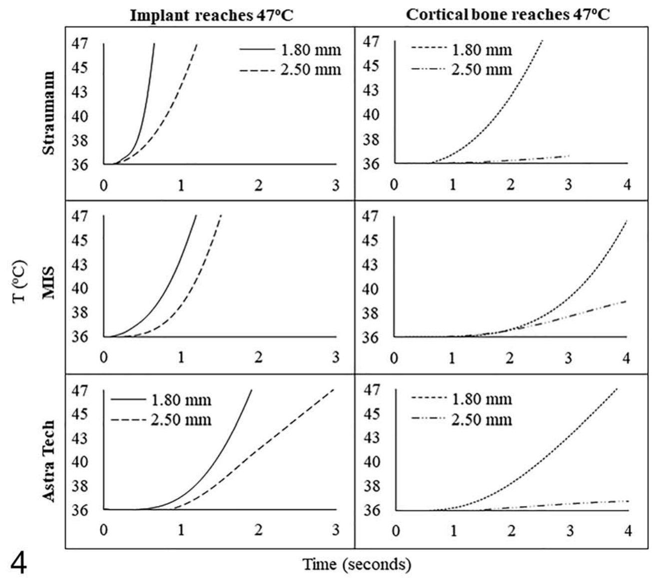

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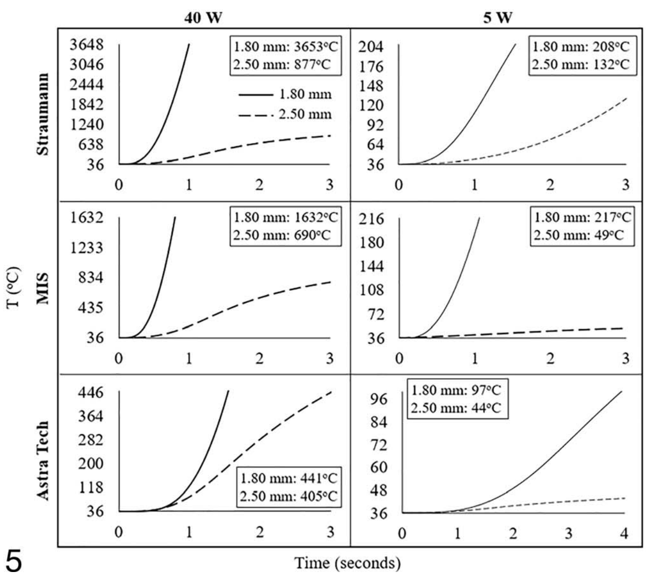

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Figures 3–5. Figure 3. The temperature increase in the implant and the cortical bone at 40 W device power. **Figure 4.** The temperature increase in the implant and the cortical bone at 5 W device power. **Figure 5.** The temperature increases of the implants when the bone reaches 47°C (insets: The exact temperatures of the implants at the point the bone reaches 47°C).

investigated. To the best of our knowledge, temperature increase in dental implants resulting from contact with electrocautery tips has been investigated experimentally only by Wilcox et al.[13] They have reported that 1-second single contact with a unipolar electrocautery tip at 5 W causes an increase of 8.87°C. We have obtained similar results with the MIS implant at 5 W and 1.80 mm tip size and with Straumann implant at 5 W and 2.50 mm tip size. Since the size of the implant or the surgical tips was not discussed, we cannot further correlate to the experimental results obtained by Wilcox et al.[13] We can assume that an implant with a similar size to Straumann or a surgical tip close to 1.80 mm was used. Furthermore, the contact durations were fixed at 1 second for single or repeated contacts. The correlation between the contact duration and the temperature increase was not studied. Lastly, the temperature increase in the bone was not studied by Wilcox et al.[13] As the results of our study demonstrated, achieving the 10°C increase in the bone may not always be possible since implants usually reach to unacceptable temperatures by the time bone reaches to 47°C. In our study, only the MIS and Astra Tech implants at 5 W power and 2.50 mm tip size were at acceptable temperatures when the bone reached 47°C (Figure 5). The Straumann implant rose to 132°C when the bone reached 47°C even with low power and large tip size.

The results of this study indicate that the size of both the implant and electrocautery tip are crucial factors for achieving controlled and limited thermal necrosis. Smaller tips cause faster temperature increase compared to larger tips under the same conditions. Similarly, smaller implants heat up faster compared to larger implants.

CONCLUSION

Thermal necrosis-aided implant removal is a promising method that may help clinical practitioners in reducing the trauma and the unnecessary bone loss during removal of osseointegrated implants. This study revealed that even very brief contacts at power settings usually used in electrosurgical procedures cause a drastic increase in implant temperature. Therefore, low power settings must be used for controlled osteonecrosis. Also implant and the tip size must be taken into consideration in deciding the duration of contact with the electrocautery tip and the implant. Larger tips are recommended for slower temperature increase and shorter contact durations are recommended for smaller implants. Systematic in vivo studies based on the parameters obtained from this study are underway to further test the applicability of the thermal necrosis aided implant removal.

Abbreviations

3D: 3-dimensional
FEA: finite element analysis
Ti6Al4V: titanium 6-aluminum 4-vanadium alloy

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Note

The authors declare no conflict of interest related to this study.

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