CLINICAL ORAL IMPLANTS RESEARCH

Georg D. Strbac
Ewald Unger
René Donner
Manfred Bijak
Georg Watzek
Werner Zechner

Thermal effects of a combined irrigation method during implant site drilling. A standardized *in vitro* study using a bovine rib model

Authors' affiliations:
Georg D. Strbac, Georg Watzek, Werner Zechner, Department of Oral Surgery, Bernhard Gottlieb University Clinic of Dentistry, Medical University of Vienna, Vienna, Austria
Ewald Unger, Manfred Bijak, Center for Medical Physics and Biomedical Engineering, Medical University of Vienna, Vienna, Austria
René Donner, Department of Radiology, Medical University of Vienna, Vienna, Austria

Corresponding author:
Georg D. Strbac
Department of Oral Surgery
Bernhard Gottlieb University Clinic of Dentistry
Medical University of Vienna
Sensengasse 2a
A-1090 Vienna, Austria
Tel.: +43 1 40070 4101
Fax: +43 1 40070 4109
e-mail: georg.strbac@meduniwien.ac.at

Key words: bone drilling, combined irrigation, dental implants, heat generation, implant drills, implant preparation, multiple temperature sensors, thermal osteonecrosis

Abstract

Objectives: The purpose of this study was to evaluate the temperature changes during implant osteotomies with a combined irrigation system as compared to the commonly used external and internal irrigation under standardized conditions.

Material and methods: Drilling procedures were performed on VII bovine ribs using a computer-aided surgical system that ensured automated intermittent drilling cycles to simulate clinical conditions. A total of 320 drilling osteotomies were performed with twist (2 mm) and conical implant drills (3.5/4.3/5 mm) at various drilling depths (10/16 mm) and with different saline irrigation (50 ml/min) methods (without/external/internal/combined). Temperature changes were recorded in real time by two custom-built thermoprobes with 14 temperature sensors (7 sensors/thermoprobe) at defined measuring depths.

Results: The highest temperature increase during osteotomies was observed without any coolant irrigation (median, 8.01°C), followed by commonly used external saline irrigation (median, 2.60°C), combined irrigation (median, 1.51°C) and ultimately with internal saline irrigation (median, 1.48°C). Temperature increase with different drill diameters showed significant differences ($P < 0.05$) regarding drill depth, confirming drill depth and time of drilling as influencing factors of heat generation. Internal saline irrigation showed a significantly smaller temperature increase ($P < 0.05$) compared with combined and external irrigation. A combined irrigation procedure appears to be preferable ($P < 0.05$) to an external irrigation method primarily with higher osteotomy depths.

Conclusions: Combined irrigation provides sufficient reduction in temperature changes during drilling, and it may be more beneficial in deeper site osteotomies. Further studies to optimize the effects of a combined irrigation are needed.

Date:
Accepted 30 July 2012

To cite this article:
Strbac GD, Unger E, Donner R, Bijak M, Watzek G, Zechner W. Thermal effects of a combined irrigation method during implant site drilling. A standardized *in vitro* study using a bovine rib model.
Clin. Oral Impl. Res. **00**, 2012, 000–000
doi: 10.1111/clr.12032

For more than 40 years, dental implants have been used for functional and aesthetic rehabilitation in patients with fully and partially edentulous jaws (Branemark et al. 1969). Today, long-term studies have shown that outcome of dental implants is highly predictable, and it is continually enhanced by treatment experience, material innovations and modifications (Dierens et al. 2012; Lang et al. 2012). Preservation of healthy bone by atraumatic surgical preparation is an essential prerequisite for primary healing leading to physiological osseointegration of dental implants (Albrektsson et al. 1981; Benington et al. 2002). Bone osteotomy with surgical drills during implant site preparation may cause mechanical damage, and high friction may also lead to heat-induced bone tissue injury (Eriksson & Albrektsson 1983). Consequently, overheating induces bone tissue necrosis, inhibits bone microcirculation and activates bone marrow macrophages, thus jeopardizing the regenerative capacity of the bone. Furthermore, these heat-induced tissue injuries endanger primary healing and osseointegration of dental implants, because of reduced initial implant stability and the maintenance for bacterial infections, thus leading to early implant failure (Yoshida et al. 2009). Hence, for improving the reliability of dental implants, heat generation during implant site drilling has been examined with great interest in several *in vivo* and *in vitro* studies in the past. It has been shown that bone tissue necrosis may occur if the critical temperature threshold of 47°C is exceeded for more than 1 min because of extended friction during implant site drilling (Eriksson & Albrektsson 1983). A temperature threshold of up to 50°C is generally accepted by findings of bone alkaline phosphate denaturation at 56°C, burning and resorption of fat cells and reduction in the blood flow between 47°C and 48°C; however, the exact critical temperature for thermonecrosis during implant site drilling is still unknown (Tehemar 1999; Benington et al. 2002; Yoshida et al. 2009; Oliveira et al. 2011). Nevertheless, it has been reported that frictional heat during implant site drilling is continuously produced and is related to multiple factors. These factors include cortical thickness, drilling speed, pressure and depth, drill sharpness, design and diameter, graduated vs. one-step drilling, intermittent vs. continuous drilling and different irrigation methods (Tehemar 1999; Chacon et al. 2006; Oliveira et al. 2011; Scarano et al. 2011). But even though well-documented studies over recent decades are available, some authors still question bone overheating in dental implant osteotomies as the cause for early implant failure and the requirement of irrigation during osteotomy to prevent bone overheating at all (Flanagan 2010). These considerations may be supported by a huge variety of testing methods with varying results in current dental literature. However, not only since Hippocrates, having been one of the first recommending irrigation to prevent heat-induced tissue injuries in bone, it has been obvious that adequate saline irrigation during osteotomies is mandatory to avoid thermal damage (Krause et al. 1982; Abouzgia & James 1997). In general, two different types of irrigation systems are common in implant dentistry, an external and an internal saline irrigation during implant site drilling. Most published investigations concerning temperature measurements during implant site drilling were mainly performed with external irrigation systems. The beneficial role of an external drill irrigation system is generally accepted; in addition, internally cooled drills were introduced in implant dentistry (Lavelle & Wedgwood 1980; Haider et al. 1993; Tehemar 1999). It is assumed that the effect of an external irrigation is mainly suitable superficially in cortical bone areas. In contrast, the effect of an internal irrigation may be more beneficial in deeper site osteotomies to reduce frictional heat (Haider et al. 1993; Tehemar 1999; Benington et al. 2002). Nevertheless, the observed advantages of an external and internal irrigation system merged in a feasible combined irrigation system during implant site osteotomies, to prevent heat-induced bone tissue injuries, have not yet been investigated in the literature.

The aim of this investigation was to evaluate temperature changes with common external and internal saline irrigation methods under standardized conditions as compared to the effects of a combined external and internal irrigation system during implant site preparation. These findings may help to gain additional basic knowledge for the purpose of developing potentially new treatment procedures during implant site drilling, which could further enhance the reliability of dental implants.

Material and methods

In vitro study design

In this study, drilling procedures were performed on bovine rib specimens to observe temperature changes during implant site osteotomies. The bovine rib *in vitro* model is an established specimen model because of its similarity to human mandibular bone regarding bone density, the relationship between cortical and cancellous bone and its thermal conductivity (Davidson & James 2000; Ercoli et al. 2004; Oliveira et al. 2011; Rashad et al. 2011). In addition, for simulating clinical conditions in human bone and for standardizing bone density and the ratio between cortical and cancellous bone in this investigation, all bovine rib specimens were taken from the VII bovine rib (Fig. 1). The fresh bovine specimens were cleaned from any soft tissue residues and were cut into equal sections from 3 to 2 cm vertical thickness to ensure equivalent samples for evaluation. The samples were embedded in clear rectangular polystyrene test boxes (No. 34160-0101; Bock, Lauterbach, Germany) with auto-polymerizing acrylic resin (SR Ivolen®; Ivoclar Vivadent, Schaan, Liechtenstein) to provide a stable base throughout the drilling procedure and were stored frozen in a sterile saline solution at −20°C for investigation (Sedlin & Hirsch 1966; Benington et al. 2002; Ercoli et al. 2004; Oliveira et al. 2011).

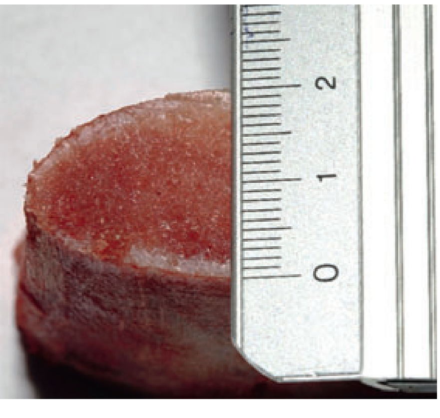

Fig. 1. Bovine specimen (VII bovine rib; vertical section).

Experimental set-up

The drilling osteotomies were performed using a special computer-aided customized surgical system (SH-Surgical Drilling-Sequence-Simulator System; Center for Medical Physics and Biomedical Engineering, Medical University of Vienna, Vienna, Austria). This customized automated unit was designed to ensure reproducible drilling cycles (parameters: dwell time, drilling feed-rate, retraction feed-rate and depth control) using a computer-aided multiphase motor, which enabled a precise vertical dislocation of the surgical contra-angle handpiece by a software-controlled program (SSH-Surgical Drilling-Sequence-Software 1.0; Center for Medical Physics and Biomedical Engineering, Medical University of Vienna). To ensure an atraumatic reproducible osteotomy with the surgical handpiece, an automated intermittent drilling procedure was simulated by means of this software program. To assure clinical conditions for this examination, the intermittent drilling software was defined in consensus with three experienced surgeons of our department for each investigation depth (10/16 mm) in a preliminary experiment (Fig. 2). The conventional surgical handpiece (WS-75 E/KM 20:1; W&H, Bürmoos, Austria) was secured with a computer-milled device, to maintain the surgical drill in a secure vertical position. This device was connected to the computer-aided sliding module of the surgical system (Fig. 3). The surgical handpiece was connected to a surgical motor unit (Implantmed SI-923, Surgical Control S-N1; W&H), which ensured constant drilling speed and constant irrigation (Oliveira et al. 2011).

Temperature measurement set-up

Thermal changes during implant site osteotomies with different irrigation methods were recorded by two custom-built thermoprobes (SHT-Thermoprobe, Center for Medical Physics and Biomedical Engineering, Medical University of Vienna, Vienna, Austria). These multichannel thermoprobes were designed with a computer-aided design (CAD) software (NX 5.0.3.2 Unigraphics, PLM Software, Siemens™; Cologne, Germany), using a standard triangulation language (STL) file for-

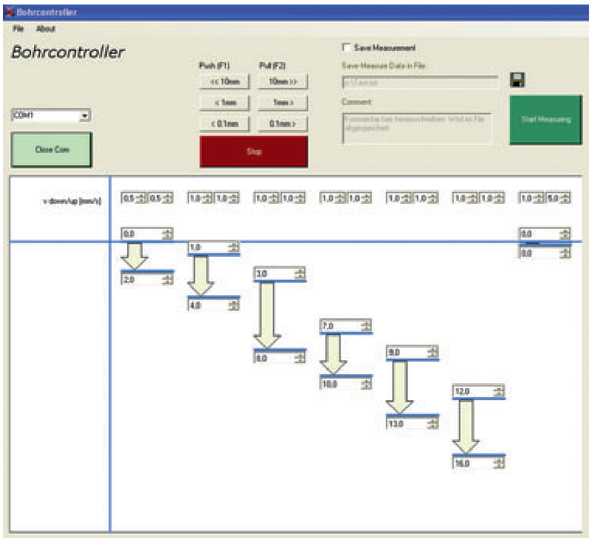

Fig. 2. Software-controlled program (SSH-Surgical Drilling-Sequence-Software 1.0; e.g., drilling depth 16 mm).

mat and were printed with a biocompatible medically approved material (Objet FullCure720^{TM}; Objet Ltd., Rehovot, Israel) by a rapid prototyping system (Objet Eden350^{TM}; Objet Ltd., Rehovot, Israel), similar to the procedure known in computer-aided implant dentistry (Moin et al. 2011). These two custom-built thermoprobes (SHT 1-Thermoprobe, SHT 2-Thermoprobe) with a diameter of 1.5 mm and a length of 18 mm were designed with 14 defined notches for the placement of 14 temperature sensors (Miniature Axial Glass Thermistor, No. GA10KM3499J15, Measurement Specialties^{TM}; Hampton, VA, USA) (Fig. 4). The 14 NTC-type temperature sensors (7 sensors/thermoprobe; NTC Sensor – Negative temperature coefficient temperature sensor; electrical resistance, 10KΩ at 25°C; diameter, 0.4 mm, hermetical glass encapsulation; temperature range, −40°C to +250°C; response time, <0.2 s), approved for medical application (e.g. blood temperature analysis, catheter devices) were placed in the custom-built thermoprobes at defined measuring depths (2, 4, 8, 10, 11, 13 and 16 mm) for temperature measurements (Fig. 5). Recording of the electrical resistance of the temperature sensors and their corresponding temperature changes during osteotomies was carried out using a computer-aided system (SHTM-Temperature Measurement System, Center for Medical Physics and Biomedical Engineering, Medical University of Vienna, Vienna, Austria), supported by an analogue measurement amplifier (SHU-Measurement Amplifier, Center for Medical Physics and Biomedical Engineering, Medical University of Vienna), an analogue-to-digital converter (ADC) (NI DAQCard^{TM}-6062E, National Instruments^{TM}; Austin, TX, USA) and a software-controlled program (DASYLab® Software 5.0; Measurement Computing Corporation, Norton, MA, USA). This computer-aided system permitted constant real-time temperature reading and digitalization of the pre-calibrated (against traceable standards; range, 5–100°C) temperature sensors at the predetermined measurement depths during osteotomies.

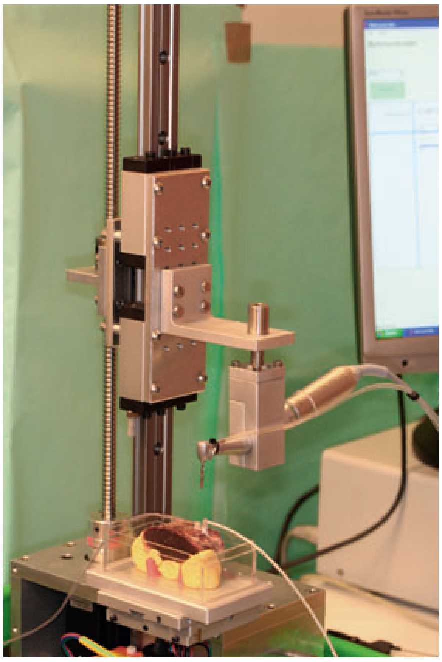

Fig. 3. Surgical system (SH-Surgical Drilling-Sequence-Simulator System) for an automated intermittent drilling osteotomy. Surgical handpiece (WS-75 E/KM 20:1, W&H) secured with a computer-milled device, to maintain the surgical drill in a secure vertical position, connected to the computer-aided sliding module of the surgical system.

Operational procedure

Before implant site osteotomies, each bovine rib specimen was maintained at room temperature (21 ± 1°C) for 3 h and wrapped in sterile isotonic saline solution gauze for hydration (Oliveira et al. 2011). The bovine rib specimens, embedded in their rectangular test boxes, were placed in a computer-milled table of the surgical device to preserve the specimens in a secure position during drilling. Prior to each drilling site assessment, placement of the two custom-built thermoprobes, parallel to the implant drill osteotomy (Fig. 5), was performed using a twist drill (diameter 2 mm, drilling depth 18 mm, 210L20.205.020, Komet®; Gebr. Brasseler, Lemgo, Germany) by precise dislocation of the table (computer-milled table with determined perforations for a precise specimen dislocation) in a predetermined distance of 1 and 2 mm to the final drill osteotomy for investigation (Jochum & Reichart 2000; Oliveira et al. 2011; Rashad et al. 2011). Before vertical insertion of the thermoprobes, a heat-transfer compound (HTCP20S 20 ml, Electrolube®; Leicestershire, UK) was injected into each thermoprobe canal to ensure an efficient heat transfer from the bone to the temperature sensors during osteotomies (Jochum & Reichart 2000; Ercoli et al. 2004; Rashad et al. 2011) (Fig. 6). The drilling procedures were performed, when the internal temperature of the specimens, as measured by two K-type sensors (Voltcraft®-PL-125-T4; Conrad Electronic SE, Hirschau, Germany), reached room temperature (21 ± 1°C) (Benington et al. 2002; Oliveira et al. 2011). Drilling speed was ensured constant at 800 rpm by the surgical motor unit, according to the recommendations of the manufacture for a standard and atraumatic surgical protocol. Reproducible automated intermittent and graduated drilling sequences with new, unused drills (NobelReplace^{TM} Tapered Drills, Nobel Biocare®; Gothenburg, Sweden) of each diameter (2mm twist drill, 3.5, 4.3 and 5mm conical implant drills) and length (10/16 mm) were performed with or without irrigation (Fig. 7). To ensure a constant irrigation of 50 ml/min isotonic saline solution (Viaflo, 0.9% NaCl, 1000 ml; Baxter Healthcare, Vienna, Austria) at room temperature (21 ± 1°C) for all three different saline irrigation methods (external/internal/combined external and internal irrigation) an irrigation tubing set (Hose set for machinery-

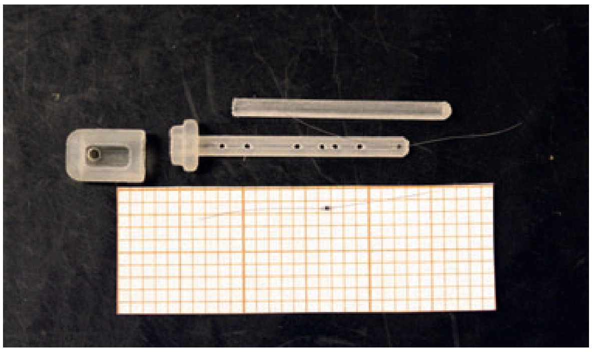

Fig. 4. Custom-built thermoprobe (SHT-Thermoprobe; ∅ 1.5 and 18 mm length) with defined notches for the placement of temperature sensors. Temperature sensor (∅ 0.4 mm, electrical resistance 10KΩ at 25°C, hermetical glass encapsulation, temperature range –40°C to +250°C, response time <0.2 s) with lead wires (Platin/Iridium) for welding.

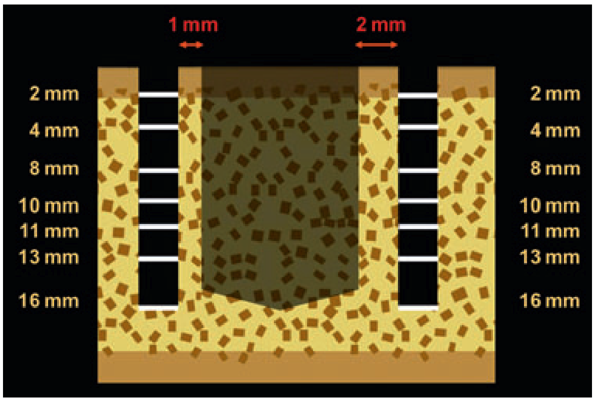

Fig. 5. Cross-sectional schematic representation of drilling site and thermoprobe positions (14 defined temperature sensor measuring depths) at a predetermined distance of 1 and 2 mm (arrows) to the final drill osteotomy.

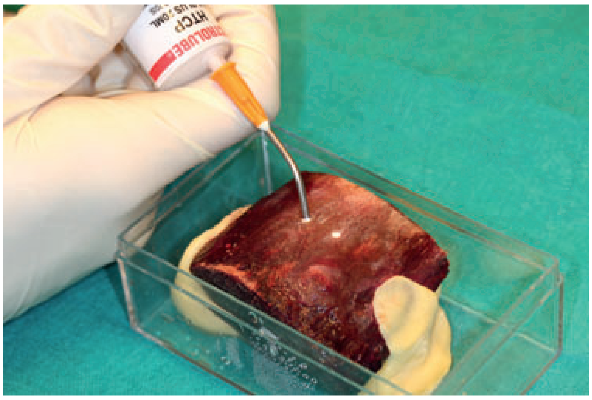

Fig. 6. Injection of a heat-transfer compound (HTCP20S 20 ml, Electrolube$^{®}$) for an efficient heat transfer during osteotomies.

80 mm, Omnia$^{®}$; Omnia S.p.A., Fidenza, Italy) was connected to the surgical handpiece. Each bovine rib specimen (in total 80 specimens) was randomly divided and perforated four times with all different irrigation methods, to reduce any bias because of different bone densities of the osseous study model (Mišić et al. 2011; Oliveira et al. 2011; Marković et al. 2012). In this investigation for each diameter (2/3.5/4.3/5 mm), drilling depth (10/16 mm) and irrigation method (without/external/internal/combined), 10 repetitions of the automated intermittent and graduated drilling sequences were conducted ($n = 320$ osteotomies in total: $n = 80$ for each diameter, $n = 160$ for each drilling depth, $n = 80$ for each irrigation method).

Statistical analysis

The temperature change of each final drill osteotomy was documented in real time by the two custom thermoprobes (predetermined distance of 1 and 2 mm), which contained 14 temperature sensors (7 sensors/thermoprobe) at defined measuring depths. The entire data (ASC file format) was recorded by the computer-aided temperature measurement system and processed by a custom analysis software program for descriptive statistics (Temperature Analysis, Department of Radiology, Medical University of Vienna, Vienna, Austria) built on a computing software program (MATLAB$^{®}$, R2011a, MathWorks$^{®}$, Natick, MA, USA). Temperature changes for each drilling osteotomy were calculated and compared by subtracting the recorded temperature [T_x] with the bone specimen baseline temperature [T_0] before each osteotomy [$\Delta T(°C) = T_x - T_0$] (Oliveira et al. 2011; Rashad et al. 2011).

Data were graphically described by boxplots or tabulated by medians, minimum and maximum. The temperature sensor location with the highest median of all 14 locations per drill was described for each combination of irrigation method, drill diameter and drilling depth and compared between 10 and 16 mm by Student's *t*-test. A *t*-test for unequal variances was used in case of unequal variances. The mean of all 14 temperature sensor location per drill was used for further analysis of irrigation method, drill diameter and drilling depth influence. A linear mixed model was estimated, which included the three factors (drilling depth, drilling diameter and irrigation method) and their interactions. The four drill holes per bovine rib were included as repeated measurements, assuming a compound symmetry variance-covariance matrix. A square-root transformation was applied to the data, so that the assumptions about residuals (normal distribution, homoscedasticity) were met. As the three-way interaction was highly significant, subgroup analyses were performed by comparison of least-square means within the linear mixed model. Effects were described by back-transformed least-square means and corresponding 95% confidence intervals (95% CI). Statistical calculations were performed with the statistical software SAS$^{®}$ (Version 9.3; SAS Institute Inc., Cary, NC, USA). All *P*-values are two-sided, and $P \leq 0.05$ was considered statistical significant.

Fig. 7. Automated intermittent and graduated drilling sequence (e.g. 4.3 mm conical implant drill, drilling depth 16 mm and combined saline irrigation) with thermoprobes (SHT 1-Thermoprobe, SHT 2-Thermoprobe).

Results

Temperature changes of 320 drilling osteotomies (10 repetitions for each diameter, drilling depth and irrigation method) at predetermined measurement depths and distances (in total, 14 temperature sensors) were evaluated. All real-time measurement sequences presented an increase in temperature in superficial cortical and deeper cancellous bone areas for all investigated methods of implant osteotomies.

The mean bone specimen baseline temperature $[T_0]$ before each osteotomy for drilling depths of 10 mm was 21.45 ± 0.36°C and for drilling depths of 16 mm 21.71 ± 0.31°C. The total intermittent processing time for each osteotomy of 10 mm was 27.6 s and for 16 mm drilling depth 43.5 s, including implant drilling and withdrawing.

The distributions of mean differences between drilling and baseline temperatures over the determined 14 temperature sensors are presented in Figs 8 and 9. The linear mixed model detected a significant three-way interaction between drilling depths, drill diameter and irrigation methods ($P < 0.0001$), and consequently subgroups were described and tested.

Maximum temperature increase during drilling with different irrigation methods

The highest temperature increase during osteotomies (Table 1) was observed without any coolant irrigation (median, 8.01°C), followed by a commonly used external saline irrigation (median, 2.60°C), combined external and internal saline irrigation (median, 1.51°C) and ultimately with an internal saline irrigation (median, 1.48°C).

Drilling sequences without irrigation

The greatest median of ΔT°C during drilling without saline irrigation was 8.01°C with conical implant drills of 3.5 mm diameter and 10 mm depth (Table 1).

There were statistically significant differences ($P < 0.01$) between mean temperature increase at 10 and 16 mm drilling depths with 2-mm twist drills and conical implant drills of 4.3 and 5 mm diameter (Table 2).

Drilling sequences with external irrigation

The highest median of ΔT°C during drilling with constant external saline irrigation (21 ± 1°C) was 2.60°C with conical implant drills of 3.5 mm diameter and 16 mm depth (Table 1).

Significant differences ($P < 0.0001$) could be observed between mean temperature increase at 10 and 16 mm drilling depths with 2 mm twist drills and conical implant drills of 3.5 and 4.3 mm diameter (Table 2).

Drilling sequences with internal irrigation

The greatest median of ΔT°C during drilling with constant internal saline irrigation (21 ± 1°C) was 1.48°C with 2-mm-diameter twist drills and 16 mm depths (Table 1).

Two millimetre twist drills ($P < 0.0001$) and conical implant drills of 5 mm diameter ($P < 0.0407$) showed statistically significant differences for ΔT°C between 10 and 16 mm drilling depths (Table 2).

Drilling sequences with combined external and internal irrigation

The highest median of ΔT°C during drilling with constant combined external and internal saline irrigation (21 ± 1°C) was 1.51°C with conical implant drills of 3.5 mm diameter and 16 mm depths (Table 1).

Significant differences could be seen between temperature increase at 10 and 16 mm drilling depths with 2-mm twist drills ($P < 0.0030$) and conical implant drills of 3.5 mm ($P < 0.0052$) diameter (Table 2).

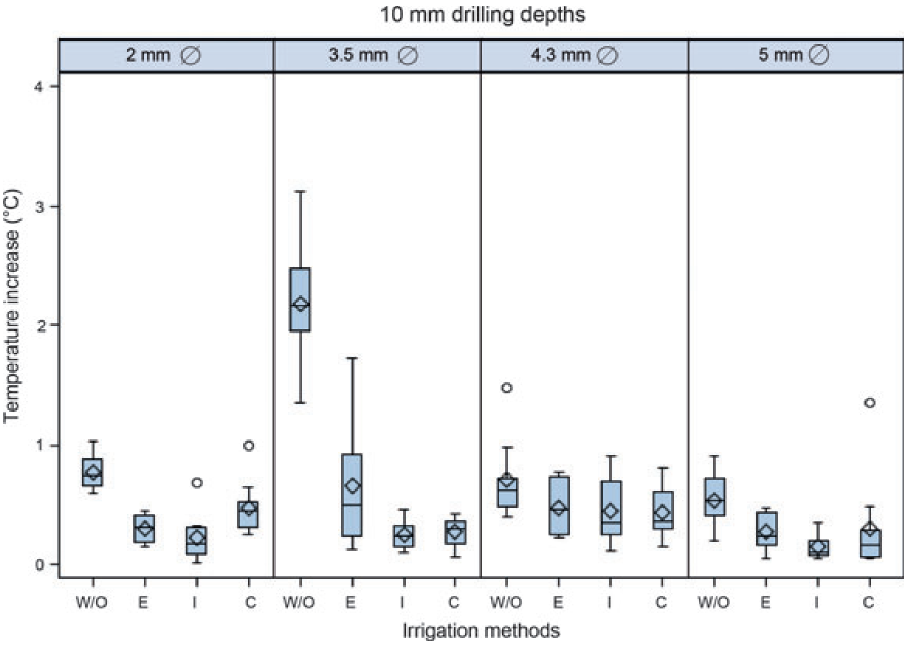

Fig. 8. Boxplots of temperature increase regarding irrigation methods (W/O, without; E, external; I, internal; C, combined irrigation) and drill diameters during drilling depths of 10 mm (diamonds indicate means).

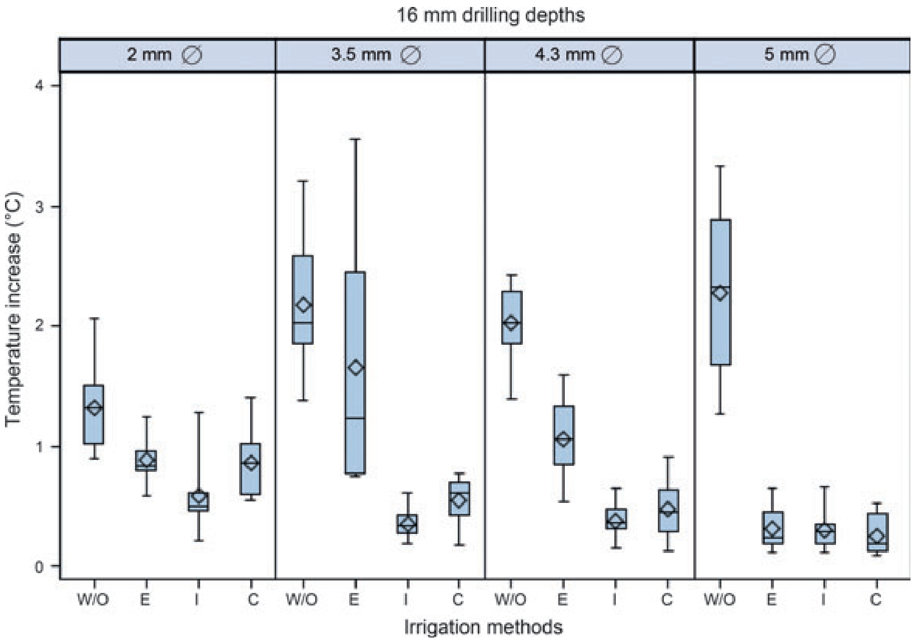

Fig. 9. Boxplots of temperature increase regarding irrigation methods (W/O, without; E, external; I, internal; C, combined irrigation) and drill diameters during drilling depths of 16 mm (diamonds indicate means).

Maximum temperature increase during drilling regarding various temperature sensor depths

During implant osteotomies all 14 temperature measurement sensors, at a predetermined distance and depth to each drill, revealed an increase in temperature in superficial and deeper bone areas for all methods investigated. Significantly higher temperature differences during osteotomies could be observed at the seven temperature measurement sensors of the thermoprobe (SHT 1-Thermoprobe), located at a distance of 1 mm, compared with the seven temperature measurement sensors of the second thermoprobe (SHT 2-Thermoprobe) placed in a distance of 2 mm to the surgical drill ($P < 0.0001$).

The highest temperature increase during drilling without irrigation was found at 4 mm temperature measurement sensor depths during 10 mm (median, 8.01°C, 3.5 mm diameter) and 16 mm (median, 5.32°C, 4.3 mm diameter) drilling osteotomies (Table 1).

The highest temperature increase during drilling with external saline irrigation was observed with drills of 3.5 mm diameter located at 4-mm temperature measurement sensors during 10 mm (median, 1.46°C) and at 8 mm measurement sensors during 16 mm (median, 2.60°C) preparation depths (Table 1).

The greatest temperature increase during drilling with internal saline irrigation was observed at 2 mm measurement depths during 10 mm (median, 0.79°C, 4.3 mm diameter) and at 4 mm measurement depths during 16 mm (median, 1.48°C, 2 mm diameter) osteotomies (Table 1).

The highest temperature increase during drilling with combined external and internal saline irrigation was recorded at 4 mm measurement depths during 10 mm (max 1.25°C, 2 mm diameter) and at 4 mm measurement sensors during 16 mm (max 1.51°C, 3.5 mm diameter) implants site preparation (Table 1).

The greatest temperature increase [ΔT] during implant site osteotomies of 10 mm drilling depths was recorded by temperature measurement sensors located between 2 and 4 mm bone layers. In contrast, the highest temperature increase [ΔT] during implant site preparation of 16 mm drilling depths was found between 2 and 11 mm bone areas for all investigated methods.

Temperature increase during drilling with different irrigation methods regarding drilling depths (10/16 mm)

During implant osteotomies at drilling depths of 10 and 16 mm with various drill diameters, significant higher temperature differences ($P < 0.05$) were recorded without any irrigation compared with the saline irrigation methods (external/internal/combined) (Table 3,Figs 8 and 9).

Drilling osteotomies of 10 mm depth

The lowest temperature increase at all measuring points, in superficial and in deeper bone areas, throughout 10 mm drilling osteotomies was obtained with internal saline irrigation during 2-mm-diameter twist drills and conical implant drills of 3.5 mm diameter ($P < 0.01$), related to external or combined irrigation. Significantly higher temperatures could be observed with external irrigation during conical implant drill preparation of 3.5 mm diameter ($P < 0.01$) and with com-

***Table 1.* Highest median temperature increase (temperature sensor depth; ΔT°C Median; [Min-Max]) over all 14 temperature sensor locations at different drilling depths with various irrigation methods, testing drilling depths 10 vs. 16 mm**

		Irrigation method			
Drill diameter	Drilling depth	Without	External	Internal	Combined
2 mm	10 mm	2 mm; 2.21 (0.08–3.25)	4 mm; 1.22 (0.57–1.66)	4 mm; 0.59 (0.08–2.33)	4 mm; 1.25 (0.58–1.73)
	16 mm	8 mm; 2.73 (1.71–3.77)	11 mm; 1.67 (1.05–2.38)	4 mm; 1.48 (0.73–1.94)	8 mm; 1.47 (0.93–2.30)
	P-value	0.1781	0.0147*	0.0173*	0.2274
3.5 mm	10 mm	4 mm; 8.01 (4.08–13.00)	4 mm; 1.46 (0.48–5.77)	2 mm; 0.68 (0.37–1.41)	2 mm; 1.14 (0.16–2.46)
	16 mm	4 mm; 3.65 (2.65–4.90)	8 mm; 2.60 (1.57–7.98)	2 mm; 0.83 (0.63–4.84)	4 mm; 1.51 (0.43–2.47)
	P-value	0.0039*	0.0917	0.4814	0.3955
4.3 mm	10 mm	4 mm; 2.46 (1.27–5.83)	4 mm; 1.25 (0.40–1.94)	2 mm; 0.79 (0.24–3.05)	2 mm; 0.64 (0.26–2.34)
	16 mm	4 mm; 5.32 (3.46–7.99)	8 mm; 1.94 (0.89–3.12)	2 mm; 0.91 (0.35–1.25)	2 mm; 1.04 (0.32–3.33)
	P-value	0.0054*	0.0443*	0.8521	0.2016
5 mm	10 mm	4 mm; 2.20 (0.68–3.39)	2 mm; 0.72 (0.17–2.82)	2 mm; 0.48 (0.21–1.14)	2 mm; 0.54 (0.17–3.02)
	16 mm	4 mm; 4.15 (2.91–6.72)	2 mm; 0.55 (0.25–2.26)	2 mm; 0.74 (0.30–1.22)	2 mm; 0.51 (0.10–1.12)
	P-value	0.0039*	0.9109	0.0917	0.9109

*$P \leq 0.05$.

Table 2. **Least-square means of temperature increase (ΔT°C LSM [95% CI]) of various irrigation methods and drill diameters, testing drilling depths 10 vs. 16 mm**

		Irrigation method			
Drill diameter	Drilling depth	Without	External	Internal	Combined
2 mm	10 mm	0.77 (0.59; 0.98)	0.29 (0.19; 0.42)	0.18 (0.10; 0.29)	0.45 (0.32; 0.61)
	16 mm	1.30 (1.06; 1.56)	0.87 (0.68; 1.09)	0.56 (0.41; 0.73)	0.84 (0.65; 1.05)
	P-value	0.0013*	<0.0001*	0.0001*	0.0030*
3.5 mm	10 mm	2.15 (1.84; 2.48)	0.57 (0.42; 0.75)	0.24 (0.14; 0.35)	0.25 (0.16; 0.38)
	16 mm	2.14 (1.83; 2.47)	1.53 (1.27; 1.82)	0.34 (0.22; 0.48)	0.53 (0.38; 0.70)
	P-value	0.9878	<0.0001*	0.2239	0.0052*
4.3 mm	10 mm	0.68 (0.51; 0.87)	0.45 (0.32; 0.61)	0.42 (0.29; 0.57)	0.41 (0.28; 0.56)
	16 mm	2.01 (1.71; 2.33)	1.03 (0.82; 1.27)	0.36 (0.24; 0.50)	0.45 (0.32; 0.61)
	P-value	<0.0001*	<0.0001*	0.5747	0.7114
5 mm	10 mm	0.52 (0.37; 0.69)	0.25 (0.16; 0.38)	0.13 (0.07; 0.22)	0.23 (0.14; 0.34)
	16 mm	2.23 (1.91; 2.57)	0.29 (0.19; 0.42)	0.28 (0.18; 0.41)	0.23 (0.14; 0.35)
	P-value	<0.0001*	0.6374	0.0407*	0.9610

$^*P \le 0.05$.

bined saline irrigation during 2 mm twist drill ($P < 0.0024$) osteotomies, compared with internal irrigation (Table 3, Fig. 8).

Drilling osteotomies of 16 mm depth

The lowest temperature increase at all measuring points during 16 mm drilling preparations was achieved with internal saline irrigation ($P < 0.05$) during 2-mm-diameter twist drills and conical implant drills of 3.5 and 4.3 mm diameter, with respect to external or combined irrigation. Significantly higher temperatures could be detected with external irrigation during conical implant drill preparation of 3.5 mm ($P < 0.0001$) and 4.3 mm diameter ($P < 0.0001$), compared with internal and combined cooling (Table 3, Fig. 9).

Discussion

Numerous studies have investigated with eminent interest the factors related to frictional heat generated during implant site drilling. Most of these studies investigating this multifactorial scenario were conducted using handheld equipment on a variety of osseous study models and mainly revealed spot temperature changes at the bone surface with infrared thermography or single thermocouples, primarily leaving the deeper aspects of the bone tissue layers unevaluated (Tehemar 1999; Benington et al. 2002; Misir et al. 2009; Sener et al. 2009; Scarano et al. 2011).

The purpose of the present investigation was to examine the benefits of an external

Table 3. **Least-square means of temperature increase (ΔT°C LSM [95% CI]) of various drilling depths and drill diameters, testing different irrigation methods**

	10 mm drilling depth				16 mm drilling depth			
Irrigation	Without	External	Internal	Combined	Without	External	Internal	Combined
2 mm ∅								
ΔT°C LSM (95% CI)	0.77 (0.59; 0.98)	0.29 (0.19; 0.42)	0.18 (0.10; 0.29)	0.45 (0.32; 0.61)	1.30 (1.06; 1.56)	0.87 (0.68; 1.09)	0.56 (0.41; 0.73)	0.84 (0.65; 1.05)
P-values								
External	<0.0001*		0.1529	0.0953	0.0104*		0.0198*	0.8055
Internal	<0.0001*	0.1529		0.0024*	<0.0001*	0.0198*		0.0362*
Combined	0.0111*	0.0953	0.0024*		0.0053*	0.8055	0.0362*	
3.5 mm ∅								
ΔT°C LSM (95% CI)	2.15 (1.84; 2.48)	0.57 (0.42; 0.75)	0.24 (0.14; 0.35)	0.25 (0.16; 0.38)	2.14 (1.83; 2.47)	1.53 (1.27; 1.82)	0.34 (0.22; 0.48)	0.53 (0.38; 0.70)
P-values								
External	<0.0001*		0.0010*	0.0021*	0.0054*		<0.0001*	<0.0001*
Internal	<0.0001*	0.0010*		0.8123	<0.0001*	<0.0001*		0.0635
Combined	<0.0001*	0.0021*	0.8123		<0.0001*	<0.0001*	0.0635	
4.3 mm ∅								
ΔT°C LSM (95% CI)	0.68 (0.51; 0.87)	0.45 (0.32; 0.61)	0.42 (0.29; 0.57)	0.41 (0.28; 0.56)	2.01 (1.71; 2.33)	1.03 (0.82; 1.27)	0.36 (0.24; 0.50)	0.45 (0.32; 0.61)
P-values								
External	0.0571		0.7320	0.7051	<0.0001*		<0.0001*	<0.0001*
Internal	0.0256*	0.7320		0.9712	<0.0001*	<0.0001*		0.3716
Combined	0.0234*	0.7051	0.9712		<0.0001*	<0.0001*	0.3716	
5 mm ∅								
ΔT°C LSM (95% CI)	0.52 (0.37; 0.69)	0.25 (0.16; 0.38)	0.13 (0.07; 0.22)	0.23 (0.14; 0.34)	2.23 (1.91; 2.57)	0.29 (0.19; 0.42)	0.28 (0.18; 0.41)	0.23 (0.14; 0.35)
P-values								
External	0.0077*		0.0808	0.7385	<0.0001*		0.8724	0.4500
Internal	<0.0001*	0.0808		0.1557	<0.0001*	0.8724		0.5516
Combined	0.0029*	0.7385	0.1557		<0.0001*	0.4500	0.5516	

$^*P \le 0.05$.

irrigation system vs. an internal irrigation system and to evaluate the advantages of both irrigation methods in a viable combined irrigation system, with a reproducible automated drilling procedure on a standardized bone specimen with multichannel temperature measurement at different tissue depths.

During all implant sequences ($n = 320$) with different irrigation methods and osteotomies with drills of varying diameter and drilling depth, the recorded temperature rise was invariably above the mean bone specimen baseline temperature in each sensor depth, and it was below the determined critical temperature threshold of 47°C, according to previous reports (Benington et al. 2002; Sener et al. 2009; Oh et al. 2011; Oliveira et al. 2011; Rashad et al. 2011; Marković et al. 2012).

The fact that significant higher temperature differences (Table 3, Figs 8 and 9) were recorded during drilling without irrigation compared with those when using saline irrigation (external/internal/combined), confirms the requirement of irrigation during osteotomy to prevent bone overheating (Krause et al. 1982; Abouzgia & James 1997; Flanagan 2010).

The mean temperature increase of all temperature sensors with various irrigation methods and drill diameters (Table 2) showed significant differences regarding the different drilling depths of 10 and 16 mm, identifying drilling depth as a factor influencing heat generation in implant osteotomies (Cordioli & Majzoub 1997; Sener et al. 2009; Oliveira et al. 2011; Sumer et al. 2011). As demonstrated by previously published findings, this also indicates that a prolonged time of drilling in deeper osteotomy depths is always directly proportional to the amount of generated frictional heat (Abouzgia & Symington 1996; Tehemar 1999; Sener et al. 2009). This could also be seen in this study as a result of an individually predefined drilling duration for investigation depths of 10 mm with 27.6 s and of 16 mm with 43.5 s.

Most of the previous studies evaluating frictional heat during osteotomies had supposed that the maximum temperature increase can be observed in the cortical bone as a result of its variable density and its lower thermal conductivity (cortical bone 0.16–0.34 W/m/K vs. cancellous bone 0.30 W/m/K) and thus only monitored the temperature effects on the surface of the cortical bone but had also used only infrared thermography or single thermocouples because of technical considerations (Clattenburg et al. 1975; Tehemar 1999; Sener et al. 2009). Recently published assessments have also evaluated superficial cortical but also deeper cancellous areas with up to three thermocouples during implant site drilling and have observed diverse temperature changes in superficial and in deeper bone layers. With these new technical options, greater heat production could be observed in deeper cancellous layers by the use of twist drills, various implant drill materials (stainless steel and ceramic drills), surgical drill guides or different implant (bone condensing vs. conventional drilling; ultrasonic vs. conventional drilling) drilling techniques (Cordioli & Majzoub 1997; Misir et al. 2009; Mišić et al. 2011; Sumer et al. 2011; Rashad et al. 2011; Marković et al. 2012). In this study, temperature changes were recorded by 14 calibrated temperature sensors at predefined measurement depths and distances to the implant site, allowing detection of an overall temperature profile. This investigation revealed a temperature increase at all temperature sensors in superficial and in deeper bone areas for all different irrigation methods. Temperature measurement sensors at bone levels between 2 and 4 mm recorded the maximum temperature increase during implant site osteotomies of 10 mm drilling depths. In contrast, the maximum temperature increase during implant site preparation of 16 mm drilling depths was found at bone levels between 2 and 11 mm (Table 1). These findings confirm recently published data using up to three thermocouples for thermal measurements and showing that implant osteotomies reveal a greater heat production in deeper cancellous layers than in superficial cortical areas (Cordioli & Majzoub 1997; Misir et al. 2009; Mišić et al. 2011; Sumer et al. 2011).

In addition and as to be assumed, temperature increase may also be affected by greater osteotomy depths if no adequate irrigation can be provided during drilling (Oliveira et al. 2011). An external irrigation method is generally accepted and most published investigations were performed with external irrigation systems. As authors and clinicians suggested that external irrigation is mainly suitable in superficial locations in cortical bone areas and internal irrigation may be more beneficial in deeper site osteotomies to reduce frictional heat, capillary surgical drills for internal irrigation were introduced in implant dentistry (Lavelle & Wedgwood 1980; Haider et al. 1993; Tehemar 1999; Benington et al. 2002; Proff et al. 2006). Nevertheless, the benefits of use of internal irrigation are still controversial as outcomes equivalent to those with external irrigation procedures have been observed in investigations using infrared thermography or single thermocouples and also because contingent clogging of the internal irrigation channel and germ contamination have been reported (Sutter et al. 1992; Benington et al. 2002; Misir et al. 2009). However, it could be verified that sufficient pre-cleaning and sterilization does not pose an infection risk with internally irrigated drills (Proff et al. 2006). Moreover, to ensure the beneficial effect of an internal irrigation in deeper site osteotomies, an appropriate intermittent drilling procedure should be used to permit constant access of an internal irrigation and to avoid the clogging effect of bone chips on the cutting edge and drill flutes (Haider et al. 1993; Tehemar 1999; Laurito et al. 2010). Hence, to combine the various beneficial effects of external and internal irrigation, authors and clinicians have previously recommended the use of a combined external and internal irrigation procedure during implant osteotomies (Haider et al. 1993; Tehemar 1999). In this investigation, the smallest temperature increase in superficial and in deeper osseous areas during drilling osteotomies of 10 and 16 mm in depth could be observed with internal saline irrigation with the use of twist and conical implant drills with various diameters. Equivalent outcomes with the internal and the external irrigation method could be observed for the use of twist implant drills and conical implant drills of 4.3 and 5 mm diameter during osteotomies of 10 mm depths and conical implant drills of 5 mm diameter during osteotomies of 16 mm depths. Under all other conditions tested with twist and conical implant drills of varying diameters and osteotomy depths, the internal and the combined irrigation procedure were shown to be superior to the external irrigation method because of a significantly smaller temperature increase during implant drilling (Table 3, Figs 8 and 9). In addition, our study could demonstrate that conical implant drills, with an appropriate intermittent and graduated drilling procedure, might be more suitable for an internal or combined irrigation permitting constant access of irrigation fluid to avoid the clogging effect of bone chips on the cutting edge and drill flutes.

Moreover, the highest temperature rise during drilling with external saline irrigation was found at the 4-mm temperature measurement sensors during 10 mm and at the 8 mm measurement sensors during 16 mm osteotomy depths. In contrast, the maximum temperature increase during drilling with internal and combined saline irrigation was seen at 2 or 4 mm measurement depths during 10 mm and at the 4 mm measurement sensors during 16 mm implant site preparation (Table 1). Our results confirm that an external irrigation method primarily reduces temperature during drilling in the superficial cortical bone areas even with an intermittent procedure, thus showing higher temperature generation in deeper cancellous bone areas with greater drilling depths. In contrast, our results confirm the considerations of authors and primarily demonstrate that an internal and a combined external and internal irrigation procedure may be more beneficial in deeper site osteotomies such as longer burs or in prolonged drilling protocols like template-guided implant bed preparations (Haider et al. 1993; Tehemar 1999; Benington et al. 2002; Misir et al. 2009; Vasak et al. 2011).

This investigation was based on the working hypothesis that a combined irrigation method would provide for various beneficial effects of an external and internal irrigation as already suggested in other previous studies. Our study was able to demonstrate that an internal irrigation appears to be superior to a combined irrigation method during an intermittent graduated drilling osteotomy. In contrast, the use of combined irrigation primarily seems to be superior to an external irrigation method at greater osteotomy depths.

Conclusion

This study demonstrates that a combined irrigation method may satisfactorily reduce temperature changes during drilling. However, to establish the combined irrigation method in implant dentistry, future observations should focus on models with different bone densities and especially on an increase in irrigation volume during combined irrigation, as this is currently divided into an external and an internal irrigation system. This future adaptation would prevent a reduction in irrigation volumes and provide equivalent quantities of irrigation fluid thus enhancing the favourable effects of an external and an internal irrigation in a combined irrigation system. In addition, these new findings may contribute towards further modification of treatment procedures during implant osteotomies, especially using surgical drill guides in template-guided implant dentistry, thus reducing mechanical and thermal injuries for an enhanced bone apposition during osseointegration.

Acknowledgement: The authors wish to thank Bernhard Bliem for his technical support, and they would like to acknowledge Martina Mittlböck, PhD, for her support in statistical analyses. Furthermore, they appreciate the valuable contribution and efforts of Dr. Katharina Giannis in revising the article critically.

The authors were funded by their institutions (Department of Oral Surgery, Bernhard Gottlieb University Clinic of Dentistry, Medical University of Vienna; Center for Medical Physics and Biomedical Engineering, Medical University of Vienna; Department of Radiology, Medical University of Vienna) and the temperature measurement analysis was funded by the EU-project Khresmoi (FP7-ICT- 2009-5/257528).

Conflict of interest

The authors declare no conflict of interest.

References

Abouzgia, M.B. & James, D.F. (1997) Temperature rise during drilling through bone. *The International Journal of Oral & Maxillofacial Implants* **12**: 342–353.

Abouzgia, M.B. & Symington, J.M. (1996) Effect of drill speed on bone temperature. *The International Journal of Oral and Maxillofacial Surgery* **25**: 394–399.

Albrektsson, T., Branemark, P.I., Hansson, H.A. & Lindstrom, J. (1981) Osseointegrated titanium implants. Requirements for ensuring a long-lasting, direct bone-to-implant anchorage in man. *Acta Orthopaedica Scandinavica* **52**: 155–170.

Benington, I.C., Biagioni, P.A., Briggs, J., Sheridan, S. & Lamey, P.J. (2002) Thermal changes observed at implant sites during internal and external irrigation. *Clinical Oral Implants Research* **13**: 293–297.

Branemark, P.I., Adell, R., Breine, U., Hansson, B. O., Lindstrom, J. & Ohlsson, A. (1969) Intra-osseous anchorage of dental prostheses. I. Experimental studies. *Scandinavian Journal of Plastic and Reconstructive Surgery* **3**: 81–100.

Chacon, G.E., Bower, D.L., Larsen, P.E., McGlumphy, E.A. & Beck, F.M. (2006) Heat production by 3 implant drill systems after repeated drilling and sterilization. *Journal of Oral and Maxillofacial Surgery* **64**: 265–269.

Clattenburg, R., Cohen, J., Conner, S. & Cook, N. (1975) Thermal properties of cancellous bone. *Journal of Biomedical Materials Research* **9**: 169–182.

Cordioli, G. & Majzoub, Z. (1997) Heat generation during implant site preparation: an in vitro study. *The International Journal of Oral & Maxillofacial Implants* **12**: 186–193.

Davidson, S.R. & James, D.F. (2000) Measurement of thermal conductivity of bovine cortical bone. *Medical Engineering & Physics* **22**: 741–747.

Dierens, M., Vandeweghe, S., Kisch, J., Nilner, K. & De Bruyn, H. (2012) Long-term follow-up of turned single implants placed in periodontally healthy patients after 16-22 years: radiographic and peri-implant outcome. *Clinical Oral Implants Research* **23**: 197–204.

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

Eriksson, A.R. & Albrektsson, T. (1983) Temperature threshold levels for heat-induced bone tissue injury: a vital-microscopic study in the rabbit. *Journal of Prosthetic Dentistry* **50**: 101–107.

Flanagan, D. (2010) Osteotomy irrigation: is it necessary? *Implant Dentistry* **19**: 241–249.

Haider, R., Watzek, G. & Plenk, H. (1993) Effects of drill cooling and bone structure on imz implant fixation. *The International Journal of Oral & Maxillofacial Implants* **8**: 83–91.

Jochum, R.M. & Reichart, P.A. (2000) Influence of multiple use of Timedur-titanium cannon drills: thermal response and scanning electron microscopic findings. *Clinical Oral Implants Research* **11**: 139–143.

Krause, W.R., Bradbury, D.W., Kelly, J.E. & Lunceford, E.M. (1982) Temperature elevations in orthopaedic cutting operations. *Journal of Biomechanics* **15**: 267–275.

Lang, N.P., Pun, L., Lau, K.Y., Li, K.Y. & Wong, M. C. (2012) A systematic review on survival and success rates of implants placed immediately into fresh extraction sockets after at least 1 year. *Clinical Oral Implants Research* **23**(Suppl. 5): 39–66.

Laurito, D., Lamazza, L., Garreffa, G. & De Biase, A. (2010) An alternative method to record rising temperatures during dental implant site preparation: a preliminary study using bovine bone. *Annali dell'Istituto Superiore di Sanita* **46**: 405–410.

Lavelle, C. & Wedgwood, D. (1980) Effect of internal irrigation on frictional heat generated from bone drilling. *Journal of Oral Surgery* **38**: 499–503.

Marković, A., Mišić, T., Miličić, B., Calvo-Guirado, J.L., Aleksić, Z. & Dinić, A. (2012) Heat generation during implant placement in low-density bone: effect of surgical technique, insertion torque and implant macro design. *Clinical Oral Implants Research* doi: 10.1111/j.1600-0501.2012.02460.x..

Mišić, T., Marković, A., Todorović, A., Čolić, S., Šćepanović, M. & Miličić, B. (2011) An in vitro study of temperature changes in type 4 bone during implant placement: bone condensing versus bone drilling. *Oral Surgery, Oral Medicine, Oral*

Pathology, Oral Radiology & Endodontics **112**: 28–33.

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

Moin, D.A., Hassan, B., Mercelis, P. & Wismeijer, D. (2011) Designing a novel dental root analogue implant using cone beam computed tomography and CAD/CAM technology. *Clinical Oral Implants Research* doi: 10.1111/j.1600-0501.2011.02359.x.

Oh, H.J., Wikesjo, U.M., Kang, H.S., Ku, Y., Eom, T.G. & Koo, K.T. (2011) Effect of implant drill characteristics on heat generation in osteotomy sites: a pilot study. *Clinical Oral Implants Research* **22**: 722–726.

Oliveira, N., Alaejos-Algarra, F., Mareque-Bueno, J., Ferres-Padro, E. & Hernandez-Alfaro, F. (2011) Thermal changes and drill wear in bovine bone during implant site preparation. A comparative in vitro study: twisted stainless steel and ceramic drills. *Clinical Oral Implants Research* **23**: 963–969.

Proff, P., Bayerlein, T., Kramer, A., Allegrini, S. Jr, Dietze, S., Fanghanel, J. & Gedrange, T. (2006) Requirements and infection prophylaxis for internally cooled implant drills. *Folia Morphologica* **65**: 34–36.

Rashad, A., Kaiser, A., Prochnow, N., Schmitz, I., Hoffmann, E. & Maurer, P. (2011) Heat production during different ultrasonic and conventional osteotomy preparations for dental implants. *Clinical Oral Implants Research* **22**: 1361–1365.

Scarano, A., Piattelli, A., Assenza, B., Carinci, F., Di Donato, L., Romani, G.L. & Merla, A. (2011) Infrared thermographic evaluation of temperature modifications induced during implant site preparation with cylindrical versus conical drills. *Clinical Implant Dentistry & Related Research* **13**: 319–323.

Sedlin, E.D. & Hirsch, C. (1966) Factors affecting the determination of the physical properties of femoral cortical bone. *Acta Orthopaedica Scandinavica* **37**: 29–48.

Sener, B.C., Dergin, G., Gursoy, B., Kelesoglu, E. & Slih, I. (2009) Effects of irrigation temperature on heat control in vitro at different drilling depths. *Clinical Oral Implants Research* **20**: 294–298.

Sumer, M., Misir, A.F., Telcioglu, N.T., Guler, A.U. & Yenisey, M. (2011) Comparison of heat generation during implant drilling using stainless steel and ceramic drills. *Journal of Oral and Maxillofacial Surgery* **69**: 1350–1354.

Sutter, F., Krekeler, G., Schwammberger, A.E. & Sutter, F.J. (1992) Atraumatic surgical technique and implant bed preparation. *Quintessence International* **23**: 811–816.

Tehemar, S.H. (1999) Factors affecting heat generation during implant site preparation: a review of biologic observations and future considerations. *The International Journal of Oral & Maxillofacial Implants* **14**: 127–136.

Vasak, C., Watzak, G., Gahleitner, A., Strbac, G., Schemper, M. & Zechner, W. (2011) Computed tomography-based evaluation of template (nobelguide)-guided implant positions: a prospective radiological study. *Clinical Oral Implants Research* **22**: 1157–1163.

Yoshida, K., Uoshima, K., Oda, K. & Maeda, T. (2009) Influence of heat stress to matrix on bone formation. *Clinical Oral Implants Research* **20**: 782–790.