Heat generation during drilling in bone before implant placement has long been recognized as a concern. Delayed healing, necrosis, and implant loss are among the complications associated with excessive heat generation. It has been advocated that when preparing bone for the placement of titanium implants, the drilling system and protocol should be designed to prevent excessive trauma and heat generation during the drilling procedure. Previous histologic studies have shown that cell death and bone necrosis can be experimentally induced by exposing living bone to thermal energy. The degree of bone damage due to thermal energy has been suggested to depend upon both the maximum temperature and the duration of exposure. For instance, using a titanium implant bone chamber, studies reported bone damage and reduced osseointegration in living rabbit bone by heating the implant 47°C to 50°C for a duration of 1 minute. Other studies, using different models of bone thermal injury, have reported that irreversible bone changes occur between 43°C and 50°C. Consequently, a threshold level of 47°C has been implicated for implant site preparation.

The bone-anchored hearing system (BAHS) is a treatment option for patients suffering conductive or mixed hearing loss or single-sided deafness. It entails a...
retro-auricular-placed titanium implant mounted with a percutaneous abutment, to which a sound processor is connected. The sound processor receives sound, converts it to vibrations, and transmits these to the cochlea via the abutment and skull, thereby bypassing the ear canal and middle ear. For BAHS, the reported implant loss rate is generally low. Admittedly, the relationship between the reported figures on BAHS implant loss/complications and thermal injury is largely unknown.

New surgical approaches for BAHS are regularly introduced, which may entail new drilling protocols. With respect to the drilling, there are many system- and protocol-related factors that may affect the heat generation, which, according to thorough literature surveys, can be listed as follows: (1) drilling speed (for BAHS, a drill speed of 1,500 to 2,000 rpm is recommended); (2) drilling protocols (single step or incremental drilling); (3) drill depth (for BAHS, an approximately 5-mm penetration depth is used); (4) drill diameter (a press-fit approach is recommended where the final drill diameter is larger than the threaded implant core diameter both below the outer diameter of the implant); (5) irrigation; (6) drill design including flute geometry; and (7) drill sharpness and cutting properties. Nevertheless, further knowledge is required regarding how different factors, and the possible interactions between them, affect the heat generation during implant site preparation.

The present in vitro study compared a conventional drill system (Ponto, Oticon Medical) with a newly developed guided drilling system (MIPS, Oticon Medical), both mimicking the two-step osteotomy procedure for an implant of 4 mm length. The aim was to compare the two drill systems with respect to cutting performance (drill force and drill torque), generation of heat, and distortion of the bone during drilling ex vivo. Further, the study aimed to evaluate the role of specific factors (irrigation and drilling procedure) with respect to the degree of heat generation in the respective drill system.

**MATERIALS AND METHODS**

A conventional method for placement of BAHS implants is a two-drill-sequence procedure, with initial drilling using a round bur and subsequent countersinking (Figs 1a and 1c to 1k). A new, flapless surgical technique, minimally invasive Ponto surgery (MIPS), for BAHS implantation, was recently introduced. Here, the drilling is performed via a cannula through a punch-biopsy incision in the skin (Figs 1b and 1l to 1s). Customized to this cannula-guided drilling approach, new drills with twist-drill design have been developed. The design and the manufacturing of the new drill was based mainly on a similar minimally invasive approach in the dental field. However, the application of this new drill system requires information and verifications on its cutting efficiency as well as the degree of heat generation in relevant models.

In the present in vitro bench study, two drilling systems were compared using closed cell polyurethane foam (REF 1522-27, Sawbones Europe), simulating hard, human bone. The human temporal bone is a diploic dense flat bone, consisting of two cortical plates, sandwiching a trabecular bone, with a density of 1.9 g/cm³ and an elastic modulus of 13.5 GPa. Although the polyurethane foam material does not fully mimic the living human temporal bone, it does provide consistent properties compared to the use of a human cadaver bone. Furthermore, it allows for controlled and standardized preparation and positioning of thermocouples and subsequent scanning, which represent a major challenge to achieve in natural viable bone. The conventional drill system (Ponto) consists of a round bur for the initial preparation of the bone and countersink drill for the subsequent widening (Fig 2a). The guided drill system (MIPS) uses a guide drill, with a twist drill design, and subsequent enlargement of the osteotomy with a widening drill, which also has a twist drill design (Fig 2b).

All drills were manufactured from stainless steel, and in addition, the drills in the guided system were coated with diamond-like carbon. All drills, instruments, and test material were provided by the manufacturer (Oticon Medical).

**Mechanical Evaluation**

The mechanical evaluation was performed in the closed cell polyurethane foam. The material was subjected to each drill with a constant feed rate of 1 mm/s and with a constant rotational speed of 2,000 rpm while measuring thrust force (the force developed in the opposite direction of feed, parallel to the axis of the drill bit) and torque, using a specially designed test rig (Torque Test Rig, Asset No. 1002, Biomekaniska Laboratoriet). The drills were tested in pairs where the respective guide drills of the conventional and guided systems were used to create the initial hole. The guide drilling was performed to full depth in one stage as opposed to the clinical situation where the guide hole is generated in a two-stage sequence (Figs 2a and 2b).

The guide drill was then exchanged to the corresponding countersink (conventional)/widening (guided) drill without making any other changes in the setup to ensure the correct alignment of the drilled holes. For both systems, five drilling procedures with a feed rate of 1 mm/s were recorded for three individual sets of drills (a total of 15 measurements of drill force...
Figs 1a and 1b  (a) The conventional drill system (Ponto) used for the linear incision technique for placing BAHS: guide drill with removable spacer (top); countersink, 4 mm (bottom).  
(b) The guided drill system (MIPS): guide drill with removable spacer (top); widening drill, 4 mm (bottom).

Figs 1c to 1k  Linear incision with tissue preservation. For the conventional system, the following steps are executed.  
(c) A 2- to 4-cm-long linear incision is made and (d) the periosteum around the surgical site is removed.  
(e) Guide drilling is performed down to 3 mm.  
(f) If the bone thickness is sufficient, the spacer is removed to prepare for a 4-mm implant.  
(g) The hole is widened with the countersink and (h) the implant is placed.  
(i) A hole in the skin over the abutment is made using a 5-mm biopsy punch.  
(j) The skin is eased over the abutment and the incision closed.  
(k) Finally, a healing cap is snapped onto the abutment and dressing is applied.

Figs 1l to 1s  Minimally invasive Ponto surgery (MIPS). The steps for the guided technique are as follows.  
(l) At the chosen site, an incision is made using a 5-mm biopsy punch.  
(m) The periosteum is removed around the surgical site.  
(n) The cannula is inserted.  
(o) Guide drilling is performed through the cannula with the guide drill.  
(p) The guide drill spacer is removed if the bone thickness allows a 4-mm-long implant.  
(q) The hole is widened with the widening drill.  
(r) The cannula is removed, and the implant placement is performed through the circular incision.  
(s) Finally, a soft healing cap is attached to the abutment and dressing is applied.
and drill torque for each type of drill). For the guided system, drilling was performed through a cannula. All drill sequences, for the mechanical evaluations, were performed without irrigation. From the obtained thrust force and torque data, the power was calculated according to the equations:

$$P_F = F \times MPS$$
$$P_T = 2\pi \times n \times T$$

where $P_F$ is thrust power, $F$ is force in Newtons, $MPS$ is feed rate in meters per second, $P_T$ is power from the torque, and $n$ is rotations per second. By calculating the area under the curves, the amount of thrust and torque energy for the drill sequences was obtained.

**Heat Generation**

This test was designed to simulate the clinical procedure involved in implant site preparation for a 4-mm-long implant. The guided drill system was evaluated with respect to heat generation and compared with the heat generated using the conventional drill system. Similar artificial bone blocks as for the mechanical evaluation were used (REF 1522-27).

The temperature was measured using thermocouples (type K, RS Components), connected to a data logger (TC-08 Data logger, PICO) allowing real-time temperature readings, with 10 measurements per second. At the planned osteotomy sites, four canals of different depths were drilled to house the thermocouples at a distance of 0.5 mm from the calculated final periphery of the osteotomy (Fig 2c). The thermocouples were secured in the canals and insulated from the outer environment with adhesive (Tack-It, Faber-Castell) applied to the canal openings. Care was taken to secure that the end of the thermocouple, using adhesive, was in contact with the bottom of the drilled canal for optimum contact between the probe and artificial bone.

A surgical drill unit and handpiece (Implantmed SI-923 Dental drill unit, Handpiece WI-75E/KM 20:1, W&H Nordic) with a drilling speed set to 2,000 rpm was used. To imitate the clinical operating situation, the guide drill and countersink of the conventional system and the guide drill and widening drill of the guided system were used sequentially in their respective cavities. In addition, to simulate the clinical situation, freehand drilling was performed by an operator (T.E.) experienced in using the systems. Thus, neither the feed rate nor the force was controlled. Each drill sequence was completed in a predetermined order and in a prespecified location in order to avoid the influence of the heat generated in a neighboring, recently drilled hole. Tap water (22°C) was perfused manually with a 20-cc syringe. For the guided system, a cannula was filled with water prior to inserting the drill, with continuous delivery of water at the top of the cannula thereafter. To prevent cooling fluid entering the osteotomy via the distal opening of the cannula, the interface between the artificial bone and the distal surface of the cannula was sealed with pressure-sensitive adhesive (Tack-It, Faber-Castell). For the Ponto system, the water was
allowed to flow directly onto the drill and the artificial bone.

Five different drilling procedures were employed for each of the drill systems (conventional and guided) with \( n = 10 \) drillings per procedure and system. After drilling five times, each drill bit was exchanged with a new virgin drill. The drilling procedures were chosen to imitate different clinical situations in the order of assumed increased heat generation due to deviation from the recommended standard procedure:

1. **DDI** (direct drilling with continuous irrigation): Drilling according to the recommended standard procedure. Direct drilling in a one-step continuous down-and-up motion during continuous irrigation and flushing of the osteotomy after removal of the drill bit from the site.

2. **DDI3** (direct drilling with idling for 2 seconds): Similar to DDI with the addition that each drill is left idling in the osteotomy (rotating at 2,000 rpm) for approximately 2 seconds after reaching the full depth.

3. **DDII** (direct drilling with impaired irrigation): Similar to DDI with the modification of impairing the irrigation (for the conventional system, water is administered to the bone bed prior to each drill step, with no continuous irrigation during drilling and no flushing of the osteotomy after removal of the drill bit; for the guided system, the cannula is filled with water prior to each drill step, with no continuous irrigation and no flushing after drilling).

4. **DDII3** (direct drilling with idling for 2 seconds and impaired irrigation): Similar to DDI but with the combination of idling (DDI3) and impaired irrigation (DDII).

5. **DD**: As a final worst-case (positive control) condition, direct, continuous drilling without irrigation.

The variation of temperature for each drilling sequence, at each position, was calculated by subtracting the obtained temperature (at each probe position) from the specimen baseline temperature (at the respective probe position) before each drill sequence started. Thermocouple measurements in materials with low thermal conductivity are highly sensitive to the distance between the heat source and the thermocouple. Therefore, after drilling, the blocks were scanned using a Zeiss Metrotom 800 computed tomograph (Carl Zeiss Industrielle Messtechnik), and the scans were imported into PTC Creo Parametric software (Release 3.0, Data Code: M100, PTC) to determine the exact distance between the thermocouple canals and the final osteotomy walls. For each measurement, the maximum temperature increase was plotted against the distance between the thermocouple canal and the final drill tract. A power trend line equation was generated, and for each measurement, the error to the equation was calculated. The temperature measurement data points could then be moved to exactly 0.5 mm, where the temperature was recalculated as the value according to the curve fit equation at 0.5 mm while considering the calculated error (Excel, Version 16.08201.2200, Microsoft). Measurements were excluded and replaced if the drill hit the thermocouples or if the drill penetrated the thermocouple canal.

**Ex Vivo Evaluation of the Cutting Performance in Natural Bone**

The quality and degree of bone damage of the drilling site (osteotomy) was evaluated by drilling in compact tibial bone from a cow cadaver. Three separate fresh-frozen tibial bone blocks were obtained from three animals from a local butcher. Two osteotomies were created in each block, one with each drill system. The two different drill systems (conventional and guided) were used with a direct drilling and irrigation procedure (DDI) (\( n = 3 \)). Immediately after the osteotomy procedure, the blocks were fixed in formalin and processed for plastic embedding in LR White plastic resin (London Resin). The blocks were then dehydrated in a graded series of ethanol and cleared in xylene followed by resin infiltration and polymerization. Each osteotomy site block was bisected longitudinally by sawing (EXAKT Apparatebau). Subsequently, the half specimen was transversely cut, midway of the length of the osteotomy, and grinded into 20- to 30-mm-thick sections. The sections were stained with toluidine blue and subjected to histologic evaluation in an optical microscope (Nikon Eclipse E600, Nikon) equipped with image software (Nikon NIS-Elements software, Nikon).

**Statistics**

The choice of 10 drilling procedures for each combination was based on the variation between groups in the preliminary data (increase of 4.1°C [SD 2.2, \( n = 15 \)]). Power analysis revealed that eight drill passes were found to provide 80% power with a 95% confidence interval if a 3°C increase in the mean maximum temperature is to be detected. The normality of data distribution was checked by Shapiro-Wilk test. A Mann-Whitney \( U \) test was run to determine the differences in force and torque between the systems. The significance of difference in heat generation changes between the subgroups of drill systems and drilling procedure was determined using independent-samples \( t \) test. For the difference between drilling procedures within the same drill system, one-way analysis of variance (ANOVA) was used to determine significance. A three-way mixed-model ANOVA was run to evaluate the effect of two drilling systems (between-subject
factor) on heat generation using a drilling procedure (DDI, DDI3, DDII, DDII3, DD) and position (A, B, C, D) (Fig 2c) as within-subject factors and including the interaction among factors. Levene’s test was used to determine homogeneity of variances between groups.

RESULTS

Mechanical Evaluation
At a constant feed rate of 1 mm/s, the mechanical evaluation of the cutting performance demonstrated that less force was required to drill into the artificial bone using the guide drill and widening drill of the guided system compared with the corresponding guide drill and countersink of the conventional system (Fig 3a). The force curve reflected the different designs of the drill. The force increased linearly when penetrating the material and then reached a plateau. For the conventional guide drills, with their round bur design, the force was thereafter approximately constant until full depth was reached (Fig 3a, conventional, guide drill). The two peaks seen for the guide drill of the guided system reflected the stepped drill configuration of this design (Fig 3a, guided, guide drill). Similarly, for both the conventional countersink and guided widening drill, a plateau was reached after the initial engagement with a linear increase of the force (Fig 3a, conventional, countersink). When the countersinking was done, the force increased again before full depth was reached. The torque was generally lower for the conventional system compared with twist drills in the guided system (Fig 3b). For the conventional guide drill, the constant low torque reflected the round bur design, with a relatively small contact area, of this drill bit (Fig 3b, conventional, guide drill). In the second drill step (countersink), the torque increased linearly until the countersinking engaged in the material, increasing the torque even further, before reaching full depth (Fig 3a, conventional, countersink). The curve for the guide drill in the guided system reflected the stepped drill design where more of the cutting edges were engaged in the material compared with the guide drill of the conventional system. The steep increase in torque for the final widening drill (guided) similarly...
reflected the straight twist drill design of the guided drill (Fig 3b, guided, widening drill).

The energy needed to generate the osteotomy was computed and compared between the two drilling protocols (Figs 3c and 3d). The mean thrust energy was significantly lower for both guided drills (guiding and widening drills) compared with the corresponding conventional drills. For the initial guide drilling step, mean work was 33.72 (1.21) Nmm and 43.64 (3.90) Nmm for the guided and conventional systems, respectively ($P < .001$). Corresponding scores for the second drill step were 5.25 (0.34) Nmm and 16.37 (6.43) Nmm for the guided and conventional systems, respectively ($P < .001$). The energy related to the torque was generally a factor of 1,000 times higher than for the energy related to the thrust. The mean torque energy was more than twice as high for the guide drill of the guided system, with a score of 17.56 (1.17) Nm, compared with the conventional guide drill with 7.69 (0.23) Nm ($P < .001$).

Heat Generation

Mean maximum temperature increases, at all positions for the different protocol and irrigation combinations, are presented in Table 1. Irrespective of position, the probe with the highest mean peak temperature increase was identified and used in the comparison between drill systems and between the different procedures (Fig 4a). For comparison, the maximum mean temperature increase across all probes is presented (Fig 4b). When the clinically recommended procedure was performed (ie, DDI), the temperature increase was significantly higher for the guided system compared with the conventional system (3.05°C [95% CI, 1.61 to 4.48], $P = .002$) at the position registering the highest mean peak temperature increase (position D, for both drilling protocols) (Fig 4a). The same analysis

### Table 1  Temperature Increase for the Two Drill Systems at Different Positions Using Different Drilling Procedures

<table>
<thead>
<tr>
<th>Drilling procedure</th>
<th>Drill system</th>
<th>Position</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>DDI</td>
<td>Conventional</td>
<td>A</td>
<td>1.18 (0.50)</td>
<td>1.81 (1.01)</td>
<td>1.80 (0.62)</td>
<td>2.43 (1.92)</td>
<td>1.80 (1.18)</td>
</tr>
<tr>
<td></td>
<td>Guided</td>
<td>B</td>
<td>5.29 (1.00)</td>
<td>5.01 (1.44)</td>
<td>4.93 (1.27)</td>
<td>5.47 (0.83)</td>
<td>5.18 (1.14)</td>
</tr>
<tr>
<td>DDIII</td>
<td>Conventional</td>
<td>C</td>
<td>4.01 (1.34)</td>
<td>3.39 (1.45)</td>
<td>5.15 (2.47)</td>
<td>6.75 (2.46)</td>
<td>4.83 (2.29)</td>
</tr>
<tr>
<td></td>
<td>Guided</td>
<td>D</td>
<td>14.80 (0.98)</td>
<td>16.33 (3.87)</td>
<td>10.46 (2.11)</td>
<td>14.62 (2.88)</td>
<td>14.05 (3.39)</td>
</tr>
<tr>
<td>DDII</td>
<td>Conventional</td>
<td>A</td>
<td>4.58 (3.53)</td>
<td>4.51 (3.86)</td>
<td>9.00 (9.19)</td>
<td>7.51 (3.60)</td>
<td>6.40 (3.52)</td>
</tr>
<tr>
<td></td>
<td>Guided</td>
<td>B</td>
<td>3.77 (1.49)</td>
<td>4.26 (3.07)</td>
<td>3.21 (1.51)</td>
<td>2.90 (0.90)</td>
<td>3.51 (1.49)</td>
</tr>
<tr>
<td>DDIII</td>
<td>Conventional</td>
<td>C</td>
<td>6.53 (3.05)</td>
<td>9.23 (4.47)</td>
<td>6.35 (3.33)</td>
<td>16.86 (8.85)</td>
<td>9.74 (6.70)</td>
</tr>
<tr>
<td></td>
<td>Guided</td>
<td>D</td>
<td>17.79 (1.83)</td>
<td>16.68 (1.63)</td>
<td>14.97 (1.13)</td>
<td>16.11 (1.87)</td>
<td>16.39 (1.88)</td>
</tr>
<tr>
<td>DD</td>
<td>Conventional</td>
<td>A</td>
<td>8.13 (3.04)</td>
<td>12.60 (3.87)</td>
<td>15.66 (4.17)</td>
<td>10.34 (3.96)</td>
<td>11.37 (5.15)</td>
</tr>
<tr>
<td></td>
<td>Guided</td>
<td>B</td>
<td>11.51 (1.86)</td>
<td>15.12 (0.65)</td>
<td>12.37 (1.87)</td>
<td>12.71 (1.57)</td>
<td>12.93 (2.03)</td>
</tr>
</tbody>
</table>

Data in bold indicate position where the highest mean temperature increase was registered. Data shown is mean temperature increase (SD) in °C.
performed on data not corrected for the probe distance yielded a similar statistical difference (2.53°C [95% CI, 0.40 to 4.66]), \( P = .023 \).

A paired \( t \) test analysis between the conventional and guided drilling systems in the DDI condition, including readings from all probes and positions, revealed a significantly higher mean temperature increase for the guided system of 5.18 (1.13)°C in comparison with the conventional protocol of 1.80 (1.20)°C (\( P < .001 \)). A significantly higher mean was also confirmed when performing the same paired analysis on the noncorrected data.

When leaving the drill idling for 2 seconds after reaching full depth (DDI3), this resulted in a significant increase of the temperature for both systems despite administering full irrigation (Fig 4). Here, the temperature increase was significantly higher for guided compared with conventional systems, when comparing the highest mean temperature increases at the probe. In contrast, in the protocol where irrigation was impaired (DDII), the opposite was revealed, with a higher increase for the conventional system compared with the guided system (conventional, 9.00 [9.19]°C vs guided, 4.26 [3.07]°C, \( P = .0004 \) (Table 1). When a procedure with a combination of impaired cooling and 2-seconds idling was used (DDI3), high comparable temperature increases were registered for both drill systems, which also matched the high temperature increases when drilling without irrigation (DD) was performed (Fig 4a). In contrast, for the combination of impaired cooling and 2-seconds idling (DDII3), when comparing the overall mean temperature increase across all probes, a significantly higher temperature increase was registered for the guided system compared with the conventional system (Fig 4b).

A three-way mixed ANOVA was run to illustrate the effects of drilling procedure and drill system on heat generation at different sites around the ostectomy (positions A to D) (Table 1). Temperatures were normally distributed, as assessed by the Shapiro-Wilk test (\( P > .05 \)). There were 11 outliers (of a total of 200 data points), as assessed by inspection of a boxplot. The outliers were kept in the analysis because they did not materially affect the results as assessed by a comparison of the results with and without the outliers. The assumption of homogeneity of variances was violated, as assessed by Levene’s test for equality of variances. However, since group sample sizes were equal, the three-way mixed ANOVA was run because of its robustness to heterogeneity of variance. There was a statistically significant three-way interaction between drill systems, drilling protocols, and position (F[4,577, 82.386] = 8.552, \( P < .001 \), partial \( \eta^2 = 0.195 \)) (Fig 9). A Greenhouse-Geisser correction was applied since the Mauchly’s test of sphericity indicated that the assumption of sphericity was violated. For both drill systems, there was a statistically significant simple two-way interaction between cooling regimen and depth (conventional; \( F[12, 108] = 6.883, P < .001 \), guided; \( F[2, 18] = 57.011, P < .001 \)). The assumption of sphericity was met for both simple two-way interaction effects, as assessed by Mauchly’s test of sphericity (\( P > .05 \)). For both drill systems, and at all thermocouple positions, the drilling procedure had a significant effect on temperature. There was no statistically significant simple main effect of position for any of the drill systems when drilling and irrigating were performed according to recommendations (DDII).

Similarly, for the guided drill system used in an impaired cooling situation (DDII), position did not have a significant effect on temperature. For all other combinations, there were statistically significant simple main effects of position for both drill systems, when drilling was left idling (DDI3) or idling in combination with impaired cooling (DDII3) and when no cooling was applied (DD) (Fig 5).

The temporal mean temperature increase at each thermocouple position during sequential drilling is illustrated in Fig 6 for all drilling procedures using the respective guided and conventional systems.

**Ex Vivo Qualitative Histologic Evaluation**

Generally, smoother and relatively more intact cut surfaces were observed in the guided system compared with the conventional system (Fig 7). At several occasions in the analyzed sections, the cutting surface after drilling with the conventional system showed distortions and cracking extending a few micrometers within the bone peripheries (Figs 7a, 7c, 7e, 7g). The distortions and cracking associated with the conventional drills were observed both in conjunction with proximity with blood vessel spaces as well as in apparently dense regions of the cortical bone (Fig 7). The few distortions observed in the guided system were mainly detected in association with nearby blood vessel spaces (Figs 7b, 7d, 7f, 7h).

**DISCUSSION**

Previous studies suggest that the temperature increase during drilling procedures in bone is affected by multiple factors.\(^1,10,17–19\) The present in vitro study provides data on the contribution of selected specific factors. Taken together, it is shown that the temperature elevation during drilling in artificial bone is influenced by the drill system design, the drilling procedure (irrigation and idling), and the site along the path of drilling. The study also indicates an important contribution of the operator performing the drill procedure.\(^5,10,17–19\)
For the drill systems evaluated here, drill parameters such as the drill point design, cutting face, flute design, diameters, and material were fixed. As determined by these design features and depending on the bone quality, there is likely a set of optimum drilling parameters (e.g., feed rate, thrust force, spindle speed) for achieving minimum heat generation.

**Mechanical Evaluation**

To characterize the possible impact of drill design on mechanical energy generated during drilling, thrust force and torque were determined for the two different drill systems. A higher thrust force was needed to feed the conventional drills through the material compared with the guided drills. This can be attributed to the twist drill design of the guided system, which more efficiently penetrates the material compared with the round bur and countersink of the conventional system. The thrust force is closely linked to the axial feed rate and the spindle speed, and even though data from the literature is inconsistent, most studies recommend a high feed rate.\(^5\)\(^,\)\(^17\) One emphasis in this study is that the thrust force and torque measurements were performed under constant feed rate and axial speed, and hence can be excluded as contributors to differences between the two drill systems.

It could be postulated that a drill design that requires less thrust force may shorten the drilling sequence, thereby generating less heat. On the other hand, the increased torque indicates an increased friction between the drill bit and the substrate. It is also possible that excessive increase in torque will risk clogging the flutes,\(^20\) resulting in a reduction of the cutting capability as well as creating microcracks in the bone. These two assumptions were not completely supported with respect to the thrust force and torque measurements in the present study. First, for the guided system, although requiring less thrust force, it was not possible to judge the reduction in drilling time/sequence, given the employed approach of using constant feed rate for specific duration of the entire drilling procedure. However, the extrapolation of mechanical findings and heat findings should be considered with care since the mechanical testing was performed without cooling. Further, although strong association is observed here between the increased torque and the increased heat generation with the guided system, the assumption that this will also lead to more mechanical damage and microcracking in the drilling site was contradicted in the histologic evaluation in the cow bone.

Even though most of the in vitro and bench experiments have been performed at controlled feed rate or controlled axial force, that has never been the case in a clinical context. For the surgeon, the thrust force contributes to the tactile feedback, and there is...
likely a large variation in applied force and, thereby, the feed rate. The procedure for placing a bone-anchored hearing implant is in most cases performed under local anesthesia, and a recent clinical report found that the overall MIPS procedure is shorter than the conventional linear incision technique. In a clinical context, the feed rate will vary, both during the actual drilling sequence and between patients, depending on several factors including the degree of bone hardness, cortical bone thickness, and the surgeon performance. During the BAHS procedure, the osteotomy created, in cortical temporal bone, is...
less than 5 mm deep, and it is performed in a single down-and-up motion. Hence, a major change of feed rate during the drilling sequence in this procedure is not expected. Nevertheless, whereas the choice of a constant feed rate of 1 mm/s was based on clinical experience, it may constitute an over-simplification in relation to potential variations in the clinical setting. Based on the findings that less thrust force was required for the penetration, using the guided system, it is possible that the shorter clinical procedure is at least in part due to the efficient and faster osteotomy site preparation. Furthermore, it is plausible that the high penetration efficiency will be advantageous for the tactile feedback of the operator and even improved comfortability for the patient.

Drilling energy is defined as the energy needed to produce a hole, and it originates from the resistance of moving the drill axially, the torque needed to cut and remove the material, and any other friction between the drill bit and the surrounding material and material chips (herein bone). In the present situation with the guided system, a possible friction between the cannula and the drill bit should also be considered. This energy is converted into heat that is dissipated to the surrounding bone, to the bone chips, to the irrigation fluid, and to the drill bit itself.\textsuperscript{21} The present study shows that the drilling energy contribution from the thrust is negligible compared with the energy used to perform the torque. Higher torque work was revealed for the guided system drills compared with the

Fig 7 Histologic evaluation of the osteotomy site. The micrographs show ground sections of the osteotomy sites created by (a, c, e, g) conventional and (b, d, f, h) guided drilling protocols.
corresponding conventional drills, resulting in a higher total energy needed to generate the hole (at the chosen feed rate of 1 mm/s and drill speed of 2,000 rpm).

Heat Generation
Two main techniques are commonly employed for real-time measurements of heat generation when drilling ex vivo in bone or in artificial bone-like materials: thermocouples or infrared thermographs. The main drawbacks with using thermocouples is the inability to generate a complete thermal profile, and more importantly, they are sensitive to distance from the heat source. To address these shortcomings, four probes positioned along the drill site were used. Moreover, after the experiment, the bone substitute blocks were scanned to verify the exact location and compensate for misalignment.

There are limitations to this study. First, although the heat transfer process is strongly dependent upon the heat generation at the drilling site and the thermal conductivity of the substrate, one limitation of the present study is the fact that the experiment was performed at room temperature rather than at body temperature. Secondly, the use of polyurethane blocks does not necessarily represent the natural temporal bone in terms of cutting characteristics and bone chip removal during drilling. Moreover, despite the thermal conductivity of the polyurethane material being similar to that of skull bone, the cooling effect of circulating blood was not considered in this test. Therefore, comparisons of the temperature increase between the different groups are more relevant than the absolute temperatures recorded.

When flapless surgery and guide drills were introduced in the dental field, there were concerns that such protocol could be more sensitive from a heat generation standpoint since the soft tissue and the guide could potentially impair the irrigation. Indeed, experimental studies conclude that preparing an implant site using surgical drill guides generates more heat than classical implant site preparation. The main drawbacks with using thermocouples is the inability to generate a complete thermal profile, and more importantly, they are sensitive to distance from the heat source. To address these shortcomings, four probes positioned along the drill site were used. Moreover, after the experiment, the bone substitute blocks were scanned to verify the exact location and compensate for misalignment.

A striking finding in this study was the sensitivity of the guided system (MIPS) to prolonged drilling (even for 3 seconds idling after reaching full penetration depth). In this situation, the mean peak temperature increase at the site with the highest increase was approximately 2.5 times higher for the guided system compared with the conventional system, despite full irrigation. In a recent experimental study measuring heat generation when drilling ex vivo in bone and artificial bone, it was suggested that the main heat source was not plastic deformation and shearing of the material at the cutting point, but rather the friction caused by the chip debris traveling through the drill flutes. This could, at least partly, explain the difference seen in the present experiment. Although definite proof is not
provided in this study, for the guided system, one assumption is that the cannula (and irrigation fluid inside the cannula) blocks the evacuation of the heated chips from the osteotomy site. In contrast, for the conventional system, the open procedure, together with the drill design, might allow for a more efficient exchange of chips and cooling fluid. However, when the irrigation is reduced, idling also influences the conventional system. Taken together, the present results show the importance of performing a drilling procedure according to recommended instructions, both with respect to irrigation but also concerning how the drilling procedure is performed. It is also worth noting the importance of flushing the drill site after drilling in order to avoid elevated temperature for prolonged periods.

CONCLUSIONS

Within the limit of this in vitro study, the results show that the level and distribution of heat surrounding the osteotomy are significantly affected by the drill design, drilling procedure, and effectiveness of irrigation. Provided the clinically recommended drilling procedure is adhered to, the absolute temperatures using either a conventional drill system or a guided drill system are below the threshold for thermally induced tissue damage. Furthermore, the results indicate that a twist drill design is more efficient and less tissue damaging compared with a conventional drill design. This study suggests that the present MIPS system for a flapless approach conveys a promising design for an efficient and still-safe osteotomy site preparation for BAHS placement.

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