in vivo *35*: 3011-3017 (2021)
doi:10.21873/invivo.12596

Review

Heat Development During Medical Drilling: Influencing Factors and Examination Methods – Overview and First Results

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Abstract. *In many medical disciplines, the process of drilling into the bone plays a crucial role for the implantation or fixation of implants or reconstruction plates. During the bone drilling process, heat is generated on the drill head and within the surrounding tissue. As a result, the increased temperature can lead to thermal damage and related necrosis of the (bone) tissue. This tissue damage is dependent on different drilling parameters and can have important influence on the following tissue healing cascade and finally on implant surveillance. In this context, the present short review elucidates the current state of scientific knowledge with regard to the heat-triggering factors during the bony drilling process and how these factors can be better understood and prevented, now and in the future, through new research approaches. External and internal influencing factors during the drilling process are distinguished and methods to examine the temperature changes are compared. This mini-review further demonstrates first preliminary results of the inflammatory tissue reactions to inadequate drilling processes. Furthermore, possible solutions of new standardized ex vivo-measurement methods to better understand the factors influencing the development of heat and to reduce animal experiments are herein discussed.*

Drilling is one of the most important and most frequently used methods in medicine and especially in dentistry to reconstruct, relieve or fixate hard tissue defects. For instance, dental drills can be used to create targeted and effective dental drillings (*e.g.*, to create implant channels for tooth implants within the jawbone).

In the beginning of the 1950s, first research results indicated that the rotation of the drill during the drilling process causes a rise of temperature in the surrounding tissue in direct dependency with the drilling speed (1). The increase in temperature during drilling is mainly caused by friction between the drill head, the bone and associated bone splinters caused by friction and by the applied pressure (2, 3). Due to the poor thermal conductivity of the bone tissue, the resulting heat accumulates in a confined space (2).

Until today, the study situation is highly inconsistent with regard to the various influencing factors (*e.g.*, internal drilling parameters such as drill configuration; external influencing factors such as cooling, feed speed and rotational speed). The limit of bone damage from heat is considered to be 47˚C (4-9). If this limit is exceeded, the suspension of the blood flow results in a reduced supply of nutrients to the affected area, which leads to bone necrosis with activation of the osteoclasts that break down the bone as well as a build-up of inferior connective tissue in the area (4, 5, 7, 8, 10-13). Clinical consequences include implant loss and fractures, leading to further surgeries and thus to an overall monetary burden on the health sector (14-17). This article is, therefore, intended to provide an introduction into the fundamentals of the various factors affecting the drilling process in order to generate basic ideas for further research efforts in this area.

This article is freely accessible online.

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Key Words: Drilling process, surgery, heat development, implants, bone tissue regeneration, review.

Influences of Different Factors

Internal factors. The internal factors influencing heat generation during the drilling process can be distinguished as follows:
Drill properties: According to Figure 1, the drill diameter, the drill shape and the drill material have the most influence on the temperature development. These are: A)

Drill diameter: The study situation is not clear. Some studies describe higher temperatures with increasing diameter, while other studies have shown higher temperatures when small diameters are used (3, 11, 18-26). B) Splinters grooves/Splinter surfaces: The size, number and angle of the chip flutes can have an influence on the temperature development. For example, a drill with three flutes and a smaller angle transports the temperature more effectively to the outside due to its higher cutting efficiency (2, 11, 14, 27, 28). In contrast, a larger angle would cause a higher temperature rise. C) Clear angle and open space: The previous study situation is not clear on this point. It can be assumed that higher clearance angles lead to lower temperatures. However, higher clearance angles in turn lead to larger open spaces, which can cause an increase in temperature (14, 29-31). Therefore, more research on this point is necessary. D) Point angles: Narrow point angles prevent the drill from slipping due to an improved attachment at the beginning of the drilling process, resulting in lower temperatures (14, 19, 29, 30, 32-35). However, narrow point angles can lead to reduced contact of the cutting surface with the bone, which can increase the drilling time and temperature. Here again, the study situation is ambiguous (14, 19, 29, 30, 32-35).

Drill alloy/coating: The alloy of the drill heads can have a major influence on the temperature increase within the (bone) tissue during the drilling process. For example, titanium-nickel-alloys cause less heat development compared to titanium-boron-nitride (36-39). Due to the large number of different alloys and coatings on the market, further studies are necessary on this point (36-39).

Wear: Multiple usage or wear of the drill leads to a stronger surface roughness and thus to higher friction and temperature increase (40-43). Clear recommendations and investigations are lacking (40-43).

External factors. External factors are considered:

Drilling speed/feed rate: The study results on this point are ambiguous. Some studies showed an inverse relationship between drilling speed/feed rate and temperature development, while other studies found higher temperatures at higher speed rates (1, 15-20, 25, 36, 40, 46-50).

Drilling energy: Drilling energy is defined as the energy required to produce a borehole. Generally, the smaller the drilling energy, the smaller the heat development. The drilling energy in turn depends on factors such as the angle applied, the applied drill or the formation of bone splinters (14, 29, 34, 35).

Cooling: Sufficient cooling and flushing can prevent a temperature rise above the limit value of 47˚C (2, 9, 35). There are different opinions or inconsistent results in the literature on the different cooling systems (internal *vs.* external cooling), the quantity to be used and the temperature of the liquid (45, 51-55).

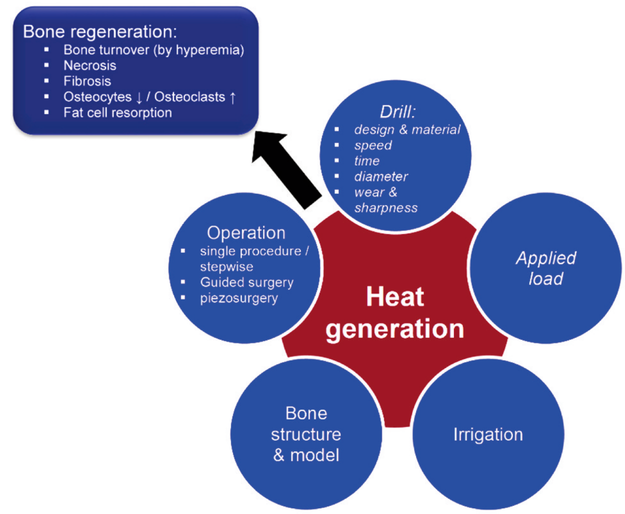

Figure 1. *Diagram of heat generation during drilling with its influencing factors and its effects on bone regeneration (44, 45).*

Drilling depth: The drilling depth depends mainly on the thickness of the cortex. The greater the drilling depth, the higher the temperature during the drilling process (3, 6, 35).

Methodology used: Some studies were able to show that a multi-stage procedure can reduce the temperature in the bone, while others showed no reduction (3, 15, 56-58). The results on the use of surgical drilling templates are inconsistent (59-61).

Patient individual factors. In addition, patient-specific factors can also have an influence on the temperature increase during the drilling process in the bone. The most important influencing factor is the bone mineral density. At a high bone mineral density, which depends on the localisation of the bone and patient-specific factors such as age and sex, significantly more heat is generated during drilling (14, 36).

Research Methods and Results

With regard to the recording and evaluating temperatures during drilling, various methods have been used. In addition to simulation using the finite element method (FEM), thermocouples, non-contact pyrometers and infrared thermography are used for metrological recording (41, 44, 62-68). The most efficient and easy-to-use methods are pyrometry and thermography, which are compared in Table I (41, 44).

Preliminary *In Vivo* Results

To analyse the influence of the drilling speed onto tissue reaction and bone tissue regeneration process, a preclinical

Table I. *Comparability of the two easiest to use non-contact temperature measurement methods in dental drilling (41, 44, 69, 70).*

Method name	Recording method	Type of temperature measurement
Pyrometry	Thermal radiation is displayed at a "radiation thermometer"	Accurate and efficient measurement of the thermal trans-mission for point like information
Thermography	Thermal radiation is displayed as a "temperature picture"	Overview of the thermal diffusion between thermocouples for imaging of an entire scene

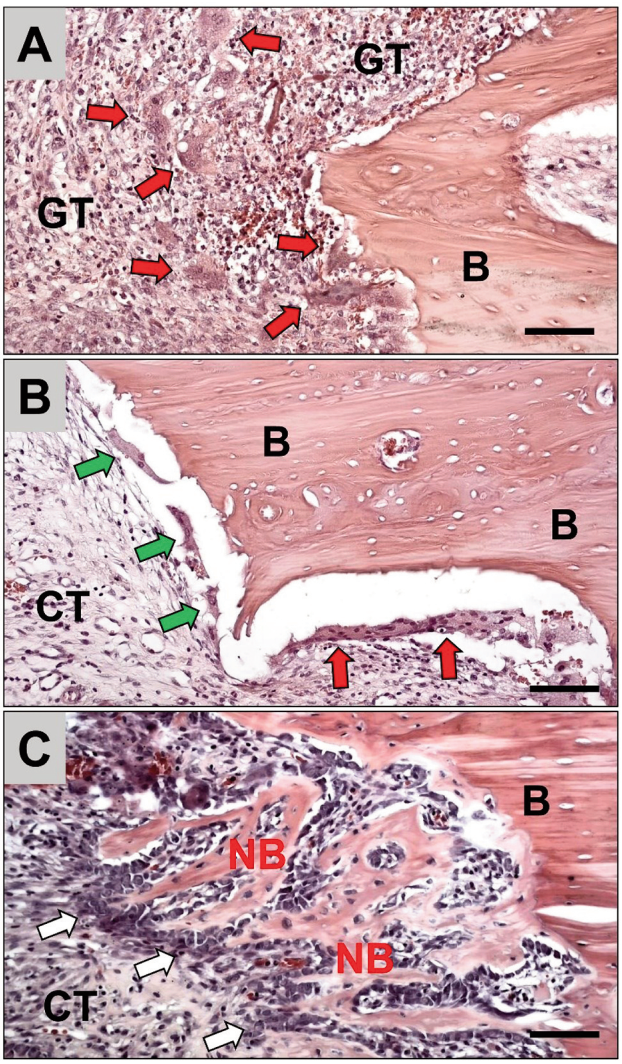

Figure 2. *Exemplary histological images showing the cellular consequences of (A) high heat, (B) medium heat and (C) low heat during drilling at day 30 after surgery. (A) The image shows that high drilling-induced heat causes a high extent of inflammation associated with development of granulation tissue (GT) and high numbers of multinucleated giant cells (MNGCs, red arrows) resorbing the neighboured bone matrix (B). (B) Medium drilling-induced heat caused a lower extent of inflammation but also MNGC-induction. CT: Connective tissue, B: bone matrix. (C) Low drilling-induced temperature allows for growth of new bone tissue (NB) with the involvement of active osteoblasts (white arrows) (HE-staining, 400× magnification, scale bars=100 μm).*

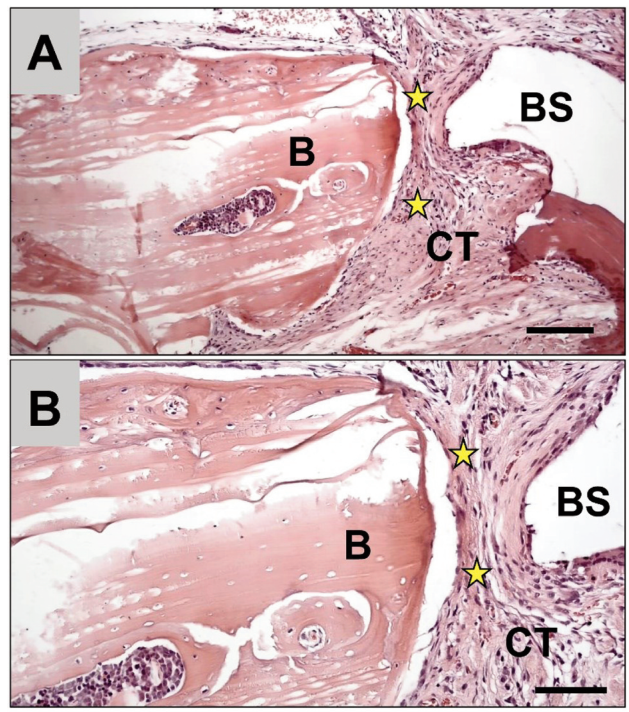

Figure 3. *Exemplary histological images showing the consequences of high heat during drilling at day 60 after surgery. The images show that high drilling-induced heat causes a fibrosis-like (yellow stars) separation of the neighbouring bone tissue (B) without any formation of new bone matrix resulting in a lack of bony integration of bone substitute granules (BS) (HE-staining, A: 100× magnification, B: 200× magnification, scale bars=100 μm).*

in vivo study was conducted based on previously published methods using the calvaria implantation model (71-75). The preliminary data reveal that the inflammatory tissue reactions increase with rises in temperature (Figure 2, Figure 3, Figure 4 and Figure 5). Thereby heat-induced damages not only lead to an inflammation-based degradation of the neighbouring bone matrix (Figure 4 and Figure 5), but also to a lack of bony integration of implants such as bone substitute materials (Figure 3). From our own experience, slight changes and consideration of the influencing factors mentioned above can have a major influence on the results.

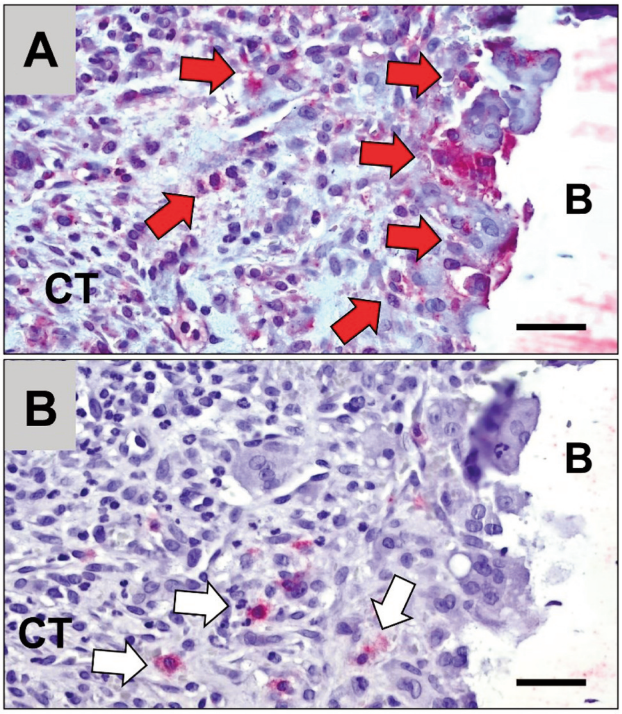

Figure 4. *Exemplary histological images showing the molecular consequences of high heat during drilling at day 30 after surgery. The images show that most inflammatory cells express the pro-inflammatory CD11-molecule (read arrows, A) but not anti-inflammatory molecules such as the CD163-molecule (white arrows, B) (immuno-staining, 400× magnification, scale bar=100 μm).*

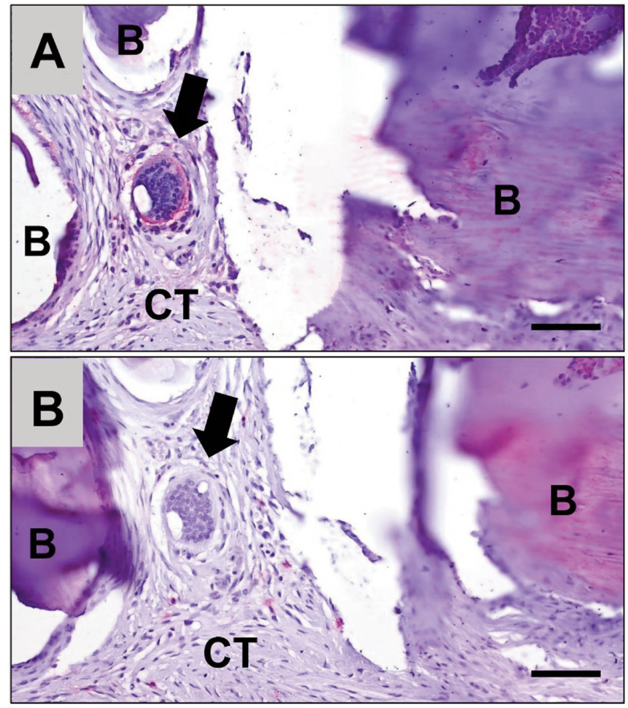

Figure 5. *Exemplary histological images showing the molecular consequences of high heat during drilling at day 30 after surgery. The images show multinucleated giant cells (black arrows in A and B) expressing the pro-inflammatory CD11-molecule (A) but not the anti-inflammatory CD163-molecule (B), presenting their inflammatory origin (immuno-staining, 400× magnification, scale bar=100 μm).*

Thereby, working with sufficient cooling fluid can prevent major necrosis in hard and soft tissue. Altogether, the data of this preclinical study present new insights into tissue injuries and their molecular basis.

Conclusion

To date, there are no uniform and consistent studies on the effects of different drilling methods or drilling factors on the surrounding tissue and the survival rate of, for example, dental implants available. It is, therefore, of great importance to investigate this topic in greater detail in order to increase operational quality and, for example, implant survival. For instance, the development of a valid *ex vivo* test bench in order to reduce or, if possible, completely avoid animal experiments in the future are of vast interest. With regard to scientific discussions on the above-mentioned parameters, a test rig can efficiently avoid animal experiments as well as accelerate and standardize scientific investigations.

The respective advantages of all the above-mentioned temperature measurement methods have to be combined with each other and the knowledge gained should be directly incorporated into the validation of new finite element method (FEM) models. Such new models can enable evaluation of the obtained data for detailed characterisation of the heat generation processes. A better understanding of the heat generation mechanisms contributes to targeted planning of experiments and can help reduce the number of animal experiments.

Conflicts of Interest

The Authors declare no conflicts of interest.

Authors' Contributions

Conceptualization, O.J. and M.B.; methodology, O.J. and M.B.; software, O.J. and M.B.; validation, O.J. and M.B.; formal analysis, O.J., C.L., S.P. and M.B.; investigation, O.J. and M.B.; resources, O.J. and M.B.; data curation, O.J., C.L., S.P. and M.B.; writing – original draft preparation, O.J., C.L., S.P. and M.B.; writing – review and editing, O.J. and M.B.; visualization, O.J. and M.B.; supervision, O.J. and M.B.; project administration, O.J. and M.B.; funding acquisition, O.J. and M.B.

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Received July 18, 2021
Revised August 21, 2021
Accepted September 7, 2021