Thermographic Evolution of Bone Temperature Evolution

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SUMMARY

Dental implants present very high long term success rates due to, among other factors, an adequate and atraumatic implant bed preparation or osteotomy. Osteotomy is a surgical procedure of bone removal where strong inflammatory reactions and trauma are present. During bone drilling, if the temperature reaches 47ºC or more for 1 minute, irreversible osteonecrosis will occur, depending on its extension on temperature magnitude and time of exposure to the thermal agent. To simulate the human jaw, fresh porcine femora of uniform density were used. To measure the temperature during bone drilling, a FLIR A325 thermal camera was used with a close-up lenses (25µm/pixel), recording one image per second. Different parameters regarding drilling speed, drilling depth, pressure applied to the drill and continuous vs intermittent drilling can induce different bone temperatures. In bone like structures a simple thermal camera is not adequate to measure temperature changes since these are extremely high and localized in very small portions of material. Therefore the use of a close-up lenses is crucial.

1. INTRODUCTION

Built primarily from collagen molecules, mineral crystals, water and ions (1) bone is a specialized connective tissue (2) that provides diverse mechanical, bio-logical and chemical functions such as structural support, protection and storage of healing cells, and mineral ion homeostasis (3).
The bone is made up of bone cells and extra-cellular matrix. The matrix consists of two types of materials - organic and inorganic. The organic matrix is formed by collagen, which represents 30-35% of the dry weight of the bone. The inorganic matrix is primarily calcium and phosphorus salts, especially hydroxyapatite [Ca10 (PO4) 6 (OH) 2] and constitutes approximately 65-70% of the dry weight of the bone. There are three main bone cell-types:
1. Osteoblasts – concerned with ossification, these cells are rich in alkaline phosphatase, glycolytic enzymes and phosphorylases.
2. Osteocytes – these are mature bone cells which vary in activity, rich in glycogen and PAS positive granules, and may assume the form of an osteoclast or reticulocyte.
3. Osteoclasts – these are multi-nucleate mesen-chymal cells concerned with bone resorption, containing glycolytic acid hydrolases, collagenases and acid phosphatase enzymes (4,5).

At the macrostructure level, bone is distinguished into the cortical (or compact) and cancellous (or trabecular) types (3). Comparison of cortical and cancellous bone demon-strates a similar matrix structure and composition, but vastly different masses, with cortical bone hav-ing a greater mass-to-volume ratio. The differences in mechanical properties between cortical and can-cellous bone are due to the differences in architec-ture, even though the composition and materials are the same. The thick and dense arrangement allows cortical bone to have a much higher resistance to torsional and bending forces, whereas cancellous bone provides greater resilience and shock absorp-tion. In general, cancellous bone is much more met-abolically active and is remodeled more often than cortical bone (6).
Cortical and cancellous bone can be made up of either woven or lamellar bone. Woven bone, some-times referred as primary bone, is seen in embryonic bone and is later resorbed and replaced by lamellar, or secondary, bone. Woven bone has a greater rate of metabolic activity compared with lamellar bone (7).
It has been demonstrated the importance of heat generation during bone drilling. About 500 BC, in his theory and practice of medicine, Hippocrates suggested that cooling should be applied to the tre-phine when disks of bone were removed from the skull (8). Necrosis around pins inserted into bone was noticed by Gillies, which he attributed to drilling heat (9).

Osseointegrated dental implants present very high long term success rates due to, among other factors, an adequate and atraumatic implant bed preparation or osteotomy (10, 11). Osteotomy is a surgical procedure of bone removal where strong inflammatory reactions and trauma are present (12). Drilling causes not only a mechanical trauma, but also a considerable thermal damage to the surrounding bone, being this the most harmful factor regarding this tissue (13). After the im-plant bed preparation and placement of the implant in its final position, several cellular and molecular events occur as a response of the wound healing process (14). Because of the low thermal conductivity of bone, heat generated during drilling is not quickly dissi-pated remaining around drill holes or osteotomies. If the temperature reaches 47ºC or more for 1 minute, irreversible osteonecrosis (15) will occur depending its extension on temper-ature magnitude and time of exposure to the thermal agent (16). Consequently, denatura-tion of alkaline phosphatase takes place (14, 15, 17, 18, 19) preventing the implant from osseointegration (15). Several factors have been described as being responsible for the temperature rising during osteotomy for implant bed preparation such as: drill speed (13, 20), pressure applied to the drill (21), drilling depth (22), irrigation (23, 24) and continuous vs intermittent perforation (24).

2. METHODS

2.1 Bone preparation

To simulate the human jaw, fresh porcine femora of uniform density and with a cortical thickness of 3-4mm were used. The porcine and canine bones best resemble human samples (25).

2.2 Drilling

All drillings were performed with the W&H Osseoset 100 dental implant motor using a 13mm long and 2mm wide cylindrical drill in new condition, running at 100 rpm with a constant load of 2.0 kg. All drilling was performed by the same surgeon.

2.3 Thermography

In order to measure the temperature during bone drilling, a FLIR A325 thermal camera was used with a close-up lenses (25μm/pixel), recording one image per second. The tests were recorded at 30Hz and analyzed af-ter using two softwares: the FLIR® thermaCAM™ Researcher 2.10 and a custom application developed in LabVIEW®.

3. RESULTS

3.1 Direct readings

When different parameters (drilling speed, drilling depth, pressure applied to the drill and continuous vs intermittent drilling) were used during bone drilling, significant differences were found regarding bone temperature. Because the aim of this study was to access if thermography is a valid method to evaluate bone temperature evolution during dental implant bed preparation, we defined a single drilling speed, with a constant pressure and without irrigation fluid.
In bone like structures, a simple thermal camera is not adequate to measure temperature changes since these are extremely high and localized in very small portions of material. Therefore, the use of a close-up lenses is crucial, which is easily demonstrated comparing fig. 1 with fig. 2, where the maximum temperatures differed more than 30ºC. (80ºC to 110ºC).

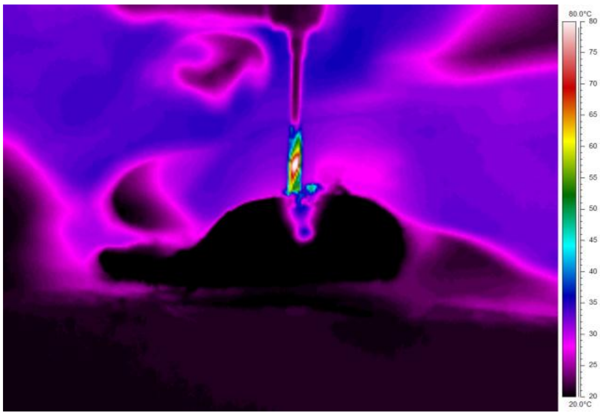

Fig. 1 - Hole drilling starting point, without close-up lenses.

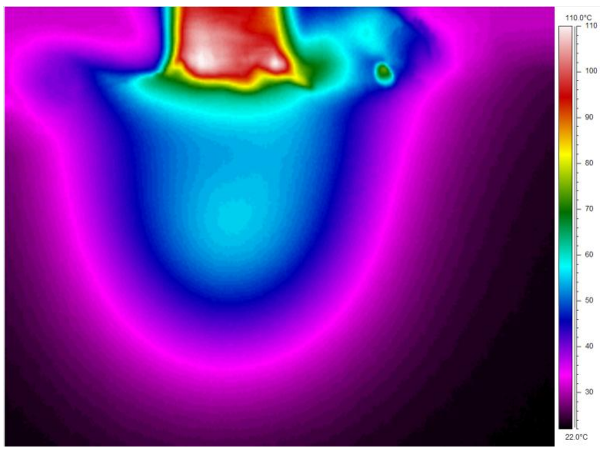

Fig. 2 - Hole drilling starting point, with close-up lenses.

As expected, during the drilling procedure, the maximum temperature was recorded in the middle of the wall. The highest temperature registered during a 15 second drilling period was 113 ±2ºC.
In what concerns to temperature patterns, these were very symmetrical along the drilling depth. This enabled another representation of the data and also other conclusions.

Fig. 3 - Temperature distribution at the end of drilling process.

3.2 Processed data

Because of the enormous symmetry in thermal patterns, it was possible to analyze only the drilling axis. Therefore, a custom application developed in LabVIEW® was used, in order to extract the temperature line that was placed in the center of the hole (Fig. 4).

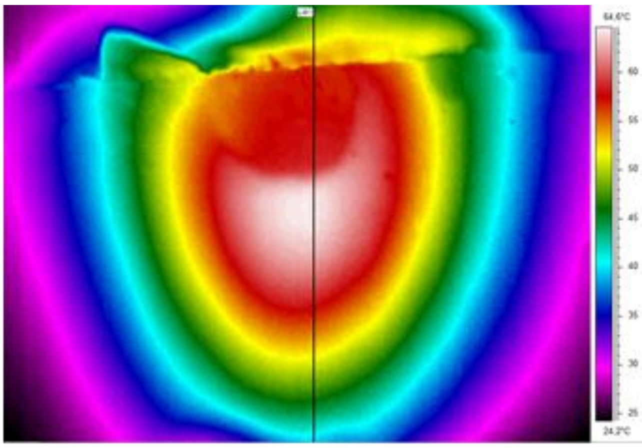

Fig. 4 - Line to analyze through time.

At each frame (recordings took place at 30Hz) and after extracting the temperature line in the center of the drill, that same line was inserted in a buffer. Then a new image was constructed, with the X axis being the time in seconds, Y the position along the drill and lastly the color representing temperature values (Fig. 5).

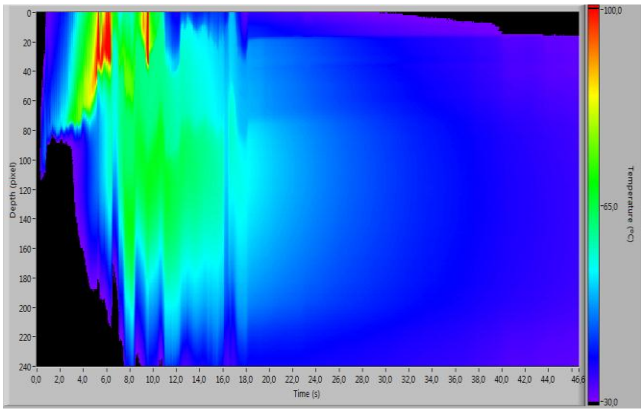

Fig. 5 - Temperature evolution (100-33 ºC).

4. DISCUSSION

During these tests, extremely high temperatures were observed, with a maximum registered of 113ºC. Considering 45º - 46ºC as the highest bone temperature before osteonecrosis occurs, bone was more than 15 seconds above 65ºC and more than 20 seconds with temperatures above recommendation (Fig. 6).
Like in all measurements with thermography also in bone drilling procedures there are inherent errors. The error of a missed estimation of the emissivity could lead to highly doubtful temperature values. This setting can be easily corrected by performing some tests with a fast response thermocouple or a RTD sensor, has a feedback for the thermal measures. There are even some references for this setting like (26).

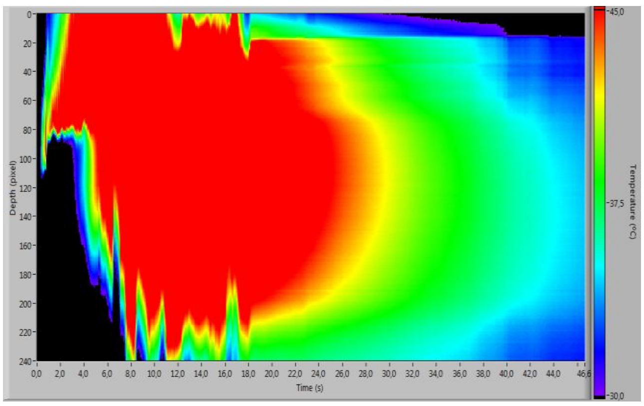

Fig. 6 - Temperature evolution (45-33 ºC).

The use of a simple thermal camera showed to be insufficient to measure the temperature of the bone during drilling procedures. To achieve a correct thermal reading is necessary to have several pixels at the same temperature to prevent neighborhood errors. Since the object of interest is relatively small, (15x15mm) a macro lenses should be required. This way, the region of interest fills the entire image and the amount of infrared radiation that reach a sensor

of the microbolometer is very resemble to their neighbor and, therefore, neighborhood errors are minimum.
One of the problems of using a macro lenses is the sensitivity to the movement during the drilling procedure; the result is illustrated in figures 5 and 6 where is visible some irregularity in the temperature border profile. In order to correct this, some extra post processing is required or, otherwise, the use of a support to firmly secure the bone sample is advisable.
Evaluating just the peak temperature is not enough, as is also extremely important to assess the temperature curves to estimate the complete bone damage. The post processing presented in figs. 5 and 6 demonstrate the alarming of unexpected high temperatures and sustenance over time.
Despite bone drilling procedures without liquid refrigeration are not recommended, under specific surgical protocols, there are implant manufacturers that advocate dry drilling perforations; these situations can be firmly reproduced in laboratory and the direct readings with thermography are enough. On the other hand, liquid refrigeration procedures cannot. Regarding this, alternative refreshing is required in a way that it does not affect the infrared radiation but able to maintain the cooling capacity of the saline solution.

5. CONCLUSION

Maximum caution must be taken during dental implant osteotomy in order to avoid bone damage that could lead to osteonecrosis and, therefore, implant failure.
The results of this study clearly indicate that a better comprehension of the drilling procedure is required so it may be determined what are the best and saffer drilling protocols.
Thermography showed to be the perfect tool to access the temperature changes and patterns during bone drilling maneuvers.
It is also necessary to develop a device that allows assessing bone drilling temperatures when liquid refrigeration is used. For example, in order to try to reproduce the same cooling capacity, a fast and directed stream of air could be an effective substitute for liquid cooling, even if the volume of air per minute could be difficult to estimate.
Further investigations are necessary to fully understand the temperature distribution and patterns during bone drilling procedures.

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