Robot-assisted dental implant surgery has become a popular alternative to classic implant placement protocols [1, 2]. The key risk factor for postoperative complications is poor compliance with surgical guidelines for implant placement, resulting in the overheating of the osteotomy site [3, 8]. Heating to over 48 °C causes a thermal burn to stromal dental tissue and protein denaturation. This prevents osseointegration between the implant and the bone and eventually leads to implant failure [4, 11].

The primary cause of an osseous burn during drilling is the wrong choice of the bone cutting and cooling modes (drilling speed >1,200 rpm, saline irrigation rate < 70 ml/min) [5, 9, 10]. During robot-assisted implant placement, saline irrigation must be performed at 100 ml/min. Drill manufacturers (Dentium, Israel; MIS, Israel; etc.) recommend that the maximum number of drill uses performed at 100 ml/min. Drill manufacturers (Dentium, Israel; MIS, Israel; etc.) recommend that the maximum number of drill uses performed at 100 ml/min. Drill manufacturers (Dentium, Israel; MIS, Israel; etc.) recommend that the maximum number of drill uses performed at 100 ml/min. Drill manufacturers (Dentium, Israel; MIS, Israel; etc.) recommend that the maximum number of drill uses performed at 100 ml/min.
The aim of this study was to measure the temperature of osseous tissue at the dental implant site during classic and robot-assisted dental implant placement performed at different cooling modes.

METHODS

The study investigated the response of the alveolar bone to osteotomy and was carried out in 15 Vietnamese pot-bellied pigs. Dental implants used in the study were cylindrical. The recipient bed was prepared by drilling using an optic implant handpiece fixed in the robotic arm; the drilling speed was 800 to 1,500 rpm.

The animals were divided into 3 groups based on the drilling speed and the type of surgical instrument (Table 1).

Before proceeding to the main part of the study, we computed the maximum optimal temperature during osteotomy for implant placement in ANSYS 19.2 (Cadfem Company; USA) (see Fig.).

The temperature of the bone matrix during osteotomy was modeled at 3 sites: the site of bur tip/bone contact, in the apical alveolar area of the prepared recipient bed and in the recipient bed immediately after removing the bur.

While modeling the temperature during osteotomy, the pressure of the drill on the bone and drilling time were assumed to be constant.

Our assessments of thermodynamic osseous tissue states confirm that an increase in the drilling speed to 1,500 rpm provokes a proportional rise in t °C to the critical threshold of 60.2 °C, given that other drilling parameters remain unchanged. An increase in the drilling speed to 1,500 rpm results in the maximum temperature gradient rising from 37.6 °C to 60.2 °C (i.e., by 22.6 °C).

Three cooling modes were tested: no irrigation, irrigation with sterile saline at 25–30 ml/min and 75 ml/min irrigation recommended by the standard surgical protocol. The temperature of the isotonic solution was 25 °C.

We also studied the response of porcine mandibular bone tissue to robot-assisted osteotomy using the device proposed in [16]. For the “robotic” part of the experiment, similar cylindrical dental implants (Dentium; Korea) were installed using a Surgic XT Plus unit with an optic implant handpiece (Japan). The following cooling modes were tested: 75 ml/min irrigation with sterile saline recommended by the standard surgical protocol, 30 ml/min irrigation and no irrigation. The temperature of the isotonic solution was 25 °C.

The pilot drill was installed in the optic handpiece; the latter was fixed in the robotic arm. Using the joystick control, the surgeon positioned the drill at the drilling site the preoperative road map. Then, the protocol for automated bone drilling was activated. Once the drilling was finished, the robotic arm retrieved the pilot drill from the mouth cavity and the pilot drill was replaced with the bed formation drill.

Temperature was measured using a Testo 104-ir infrared probe thermometer (Testo AG; Germany). Prior to the experiment, the skeletonized porcine mandible was exposed to distilled water (t = 45 °C) for 10 min. The temperature of the osteotomy site before drilling was 36.8 °C.

The majority of the installed implants were in quadrants 3 (6 implants, 60%) and 4 (4 implants, 40%) in group 1; quadrants 3 (7 implants, 70%) and 4 (3 implants, 30%) in group 2; quadrants 3 (5 implants, 50%) and 4 (5 implants, 50%) in group 3.

During the experiment on the mandibular bone tissue of pigs, we took temperature measurements of the bone matrix at the osteotomy site. For the cooling mode 3, the peak temperature was as high as 61.5 °C. For the cooling mode 2, the maximum temperature was 52 °C. The optimal temperature (39.1 °C) was achieved in the cooling mode 1.

The study investigated the response of the alveolar bone to osteotomy and was carried out in 15 Vietnamese pot-bellied pigs. Dental implants used in the study were cylindrical. The recipient bed was prepared by drilling using an optic implant handpiece fixed in the robotic arm; the drilling speed was 800 to 1,500 rpm.

Table 1. Bone cutting modes during recipient bed preparation

| Group | Instrument           | Drilling speed, rpm | Number of installed dental implants | Implant sites and number (in brackets) |
|-------|----------------------|---------------------|------------------------------------|----------------------------------------|
| 1     | Lindemann guide drill| 800                 | 10                                 | 3.5 – 2, 4.6 – 3, 3.6 – 2, 3.2 – 1, 4.1 – 1, 3.3 – 1 |
|       | Lindemann pilot drill| 800                 |                                    |                                        |
|       | Harvest drill        | 800                 |                                    |                                        |
|       | Cortical drill       | 600                 |                                    |                                        |
|       | Transfer piece       | 30–45 Ncm           |                                    |                                        |
| 2     | Lindemann guide drill| 1,200               | 10                                 | 3.4 – 2, 4.5 – 1, 3.3 – 3, 3.2 – 1, 4.2 – 2, 3.1 – 1 |
|       | Lindemann pilot drill| 1,200               |                                    |                                        |
|       | Harvest drill        | 1,200               |                                    |                                        |
|       | Cortical drill       | 1,000               |                                    |                                        |
|       | Transfer piece       | 30–45 Ncm           |                                    |                                        |
| 3     | Lindemann guide drill| 1,500               | 10                                 | 3.6 – 2, 4.2 – 1, 3.3 – 2, 4.2 – 1, 4.5 – 3, 4.6 – 1 |
|       | Lindemann pilot drill| 1,500               |                                    |                                        |
|       | Harvest drill        | 1,500               |                                    |                                        |
|       | Cortical drill       | 1,200               |                                    |                                        |
|       | Transfer piece       | 30–45 Ncm           |                                    |                                        |
The relative reduction in the rate of negative outcomes in the main vs control groups, i.e. relative risk reduction, was 400%. This value, along with the 95% CI, means that the effect is clinically significant (Table 3).

### RESULTS

The temperature of the osteotomy site in the mandible rose to 41.3 °С from the initial value of 36.8 °С after 5 seconds of drilling in Table 2.

![Fig. Modeled temperature during osteotomy for dental implant placement. A. Temperature gradient from 22 °С to 37.6 °С (800 rpm). B. Temperature gradient from 22 °С to 51.9 °С (1,200 rpm). C. Temperature gradient from 22 °С to 60.2 °С (1,500 rpm).]

**Table 2. Peak temperature during osteotomy for dental implant surgery at different cooling modes**

| Cooling modes | Drilling parameters | Bone temperature at the osteotomy site (°С) | Drilling time (s) |
|---------------|---------------------|---------------------------------------------|------------------|
| Mode 1        | 800                 | 39.1 ± 0.22                                 | 45               |
| Mode 2        | 1,200               | 52 ± 0.37                                   | 45               |
| Mode 3        | 1,500               | 61.5 ± 0.43                                 | 45               |

**Table 3. Efficacy of dental implant surgery according to evidence-based medicine criteria**

| Group   | Positive clinical outcome | Yes  | No  | Total |
|---------|----------------------------|------|-----|-------|
| Main    |                           | 5    | 0   | 5     |
| Control |                           | 15   | 0   | 15    |
| RO      | 100.00%                   |      |     |       |
| RNO     | 20.00%                    |      |     |       |
| RR      | 500.00%                   |      |     |       |
| RRR     | 400.00%                   |      |     |       |
| CAP     | 80.00%                    |      |     |       |
| NNT     | 1.3                       |      |     |       |
| Odds (main group) |                        |      |     |       |
| Odds (control group) |                      | 0.3  |     |       |
| OR      |                          |      |     |       |

Note: RO — rate of outcomes; RNO — rate of negative outcomes; RR — relative risk; RRR — relative risk reduction; NNT — number of patients that must be treated to prevent 1 negative outcome; OR — odds ratio.
the absence of irrigation during the classic dental implant placement procedure. Irrigation at 30 ml/min during 5 s of drilling resulted in a lower temperature at the recipient bed site (39.4 °C). With irrigation at 75 ml/min, the bone tissue temperature was 36.9 °C.

During recipient bed preparation, which involved bone drilling for 10 s, the bone matrix was heated to 51.5 °C in the absence of irrigation, 43.2 °C at < 30 ml/min irrigation and 39.6 °C at 75 ml/min irrigation recommended by the standard surgical protocol. Heating to over 45 °C causes irreversible changes to bone matrix.

Similar to the classic surgical protocol applied in the first part of the study, the robot-assisted protocol involved placement of cylindrical dental implants in the skeletonized portion of the mandible. The initial temperature of the mandible was close to human body temperature (36.8 °C). In the absence of irrigation, the bone temperature at the osteotomy site rose to 42.4 °C. When irrigation of the osteotomy site was delivered at < 30 ml/min during 5 seconds of bone drilling, the temperature of the osseous tissue at the osteotomy site was 38.2 °C. With irrigation at 75 ml/min, the temperature at the osteotomy site was 37.1 °C.

During the preparation of the recipient bed, which involved drilling for 10 s, the bone matrix was heated to 53.9 °C in the absence of irrigation, 45.7 °C (insufficient irrigation) and 38.9 °C (sufficient irrigation according to the standard surgical protocol).

**DISCUSSION**

At present, there is no consensus on the optimal drilling speed. According to early reports, bone temperature rose proportional to the drilling speed [17]. However, later studies revealed that this was true only for the drilling speed of 10,000 rpm [18]. None of the studies revealed any significant changes in the temperature of a human cadaver bone during drilling at 345–2,900 rpm. This means that a temperature rise was dependent on drilling pressure more than on drilling speed. It was demonstrated that low-speed, minimal-pressure drilling of bovine cortical bones caused the same rise in temperature as drilling at higher speed and higher pressure. It is high drilling speed and pressure that allow osteotomy to be performed effectively [19]. At drilling speed below 250 rpm, bone tissue gets fragmented at the edge of the defect.

**CONCLUSIONS**

The analysis of osseous tissue thermometry data obtained during osteotomy for the subsequent placement of cylindrical dental implants revealed that both classic and robot-assisted dental implant placement techniques can be recommended for clinical use and are safe if there is sufficient irrigation and good compliance with the surgical protocol.

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