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Notched K-wire for low thermal damage bone drilling

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ABSTRACT

The Kirschner wire (K-wire) is a common bone drilling tool in orthopedic surgery to affix fractured bone. Significant heat is produced due to both the cutting and the friction between the K-wire and the bone debris during drilling. Such heat can result in high temperatures, leading to osteonecrosis and other secondary injuries. To reduce thermal injury and other high-temperature associated complications, a new K-wire design with three notches along the three-plane trocar tip fabricated using a thin micro-saw tool is studied. These notches evacuate bone debris and reduce the clogging and heat generation during bone drilling. A set of four K-wires, one without notches and three notched, with depths of 0.5, 0.75, and 1 mm, are evaluated. Bone drilling experiments conducted on bovine cortical bone show that notched K-wires could effectively decrease the temperature, thrust force, and torque during bone drilling. K-wires with notches 1 mm deep reduced the thrust force and torque by approximately 30%, reduced peak temperatures by 43%, and eliminated blackened burn marks in bone. This study demonstrates that a simple modification of the tip of K-wires can effectively reduce bone temperatures during drilling.

1. Introduction

Kirschner wires or K-wires, introduced in 1909 by Martin Kirschner, are sharpened stainless steel pins widely used in orthopedics and other medical and veterinary surgical procedures [1,2]. K-wires come in different sizes and a variety of tip geometries, among which the most frequently used are the diamond (four-plane) and trocar (three-plane) tips with diameters ranging from 1 mm to 3.5 mm. The main functions of a K-wire is to penetrate and hold bone fragments together (pin fixation), to provide an anchor for skeletal traction and temporary joint immobilization, or for definitive fixation in cases of small fracture fragments [3]. Typically, the K-wires are driven into the bone through the skin (percutaneous pin fixation) using a power or hand drill and are removed once a fracture heals (typically 2–4 months later).

As K-wires are used to mechanically penetrate parts of the human body, worn, inefficient cutting edges or improper operation by surgeons can increase the risk of both traumatic and thermal injuries to the bone and adjacent neurovascular structures [4,5]. For bone drilling using K-wires, debris becomes powdery, developing friction between the wire and the drill, potentially even jamming the K-wire as the compacted debris produces large resistive and frictional forces [4,6]. Frictional forces caused by jammed, compacted bone debris and axial loading by the orthopedic surgeon conspire to create a significant amount of heat during bone drilling. Fig. 1(a) and (b) shows a trocar K-wire and an ex-vivo bovine bone sample after drilling with a feed rate of 1 mm/s at a rotational speed of 1000 rpm, typical values in bone drilling procedures [7]. The hole surface in the bone sample shows characteristic heat damage – blackening – from the high temperatures developed during K-wire drilling. In this case, the peak temperature measured 2 mm away from the hole center (1 mm from hole surface), illustrated in Fig. 1(c), exceeds 120 °C. The poor debris evacuation and lack of sharp cutting edge were responsible for such high drilling temperature [8,9]. In operating rooms during orthopedic surgery, smoke is often observed or smelled. Due to the excessive heat generated during K-wire bone drilling, osteonecrosis is a common complication, which results in the temporary or permanent loss of blood supply to the bone. This absence of blood has been shown to result in bone death, collapse, and non-healing. Experimentally, temperatures above 70 °C have been seen to result in immediate bone death, whereas irreversible cell death of osteocytes occurs after 30 s at a temperature of 55 °C and after 60 s at 47 °C [10–13]. Thermal osteonecrosis results in weaker bone with

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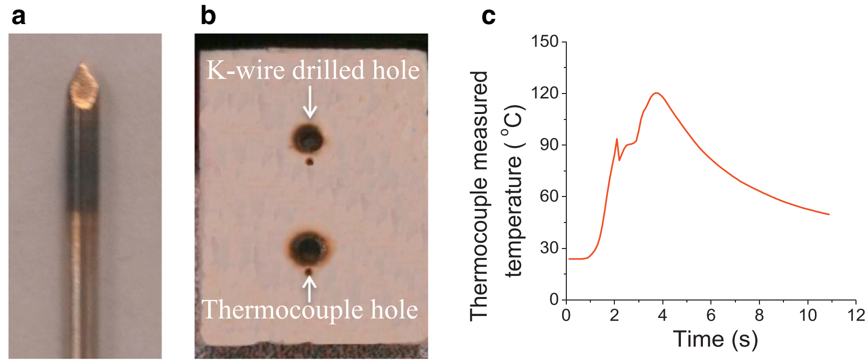

Fig. 1. (a) A three-plane trocar K-wire after drilling, (b) bovine bone sample after drilling, and (c) bone temperature measured by thermocouple at a microhole (1 mm from the hole surface) during the K-wire bone drilling [7].

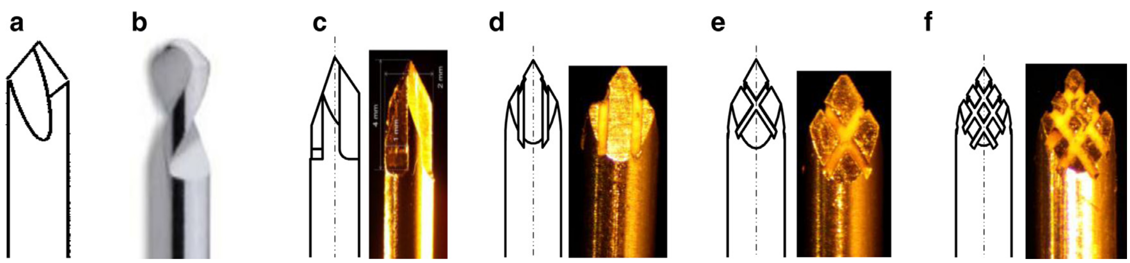

Fig. 2. The modified K-wire tips with: (a) two steep flutes [20], (b) two short flutes [21], (c) a slot [8], (d) two parallel channels [9], (e) single knurling channel [9], and (f) double knurling channels [9].

less potential to heal post-operation. K-wire that leads to lower drilling temperature is needed for the orthopedic surgery and will help the recovery and quality-of-life for patients.

There exists a wide range of literature relevant to this work, looking to quantify the temperature, force and torque in bone drilling. Augustin et al. [11] found that the increase in drill diameter and drill speed caused the increase in bone temperature using three uncoated stainless steel drills 2.5, 3.2 and 4.5 mm in diameter. Karaca et al. [12] learned that the bone temperatures increased with increased drill speeds and decreased with a higher feed rate using the stainless steel drill coated with TiBN. Lee et al. [13] presented that the maximum bone temperature increased with the high spindle speed and low feed rate using the carbide drill bits. Karaca et al. [14] used the statistical and histopathological analysis to investigate the bone temperature and observed the temperature increased with an increasing drill speed and decreased with high feed-rates and thrust forces. Lee et al. [15] presented a thermal model for bone drilling and found the maximum temperature increased with increasing spindle speed, increasing feed rate, decreasing drill-bit diameter, increasing point angle, and decreasing helix angle. Alam et al. [16] found ultrasonically-assisted bone drilling could reduce the drilling thrust force and torque. Franssen et al. [17] compared bone drilling using K-wires with 30° and 60° tip angle which resulted in 50 and 45 °C, respectively, increase in temperature 1 mm away from the hole surface. Palmisano et al. [18] conducted sequential K-wire drilling of nine holes in a 3 × 3 array on a cadaver tibia bone kept at an average body temperature (about 37 °C) under an initial moistened condition. Results showed the temperature rise increased from 5 °C at the first hole to 20 °C by the sixth hole and remained at a similar magnitude through the ninth hole. Tai et al. [19] gave a thermal damage criterion according to these experimental results and applied the finite element analysis (FEA) to predict the area of thermal damage during sequential drilling.

Several modified K-wires, as shown in Fig. 2, have been studied to evaluate the potential to reduce bone temperature in drilling. Piska [20] compared regular K-wire with a Medin K-wire (shown in Fig. 2(a)) which has two steep flutes with 20° rake angle and 30° clearance angle. Results of drilling porcine bone showed the thrust force and torque were reduced by 63% and 60%, respectively, and the average bone temperature after drilling 30 holes decreased from 129 °C (regular K-wire) to 66 °C (Medin K-wire). A commercial K-wire by Smith & Nephew [21] (Fig. 2(b)) has a short segment of spiral flute at the tip and claims to be capable of decreasing temperature and enabling faster bone drilling. Furthermore, the experiment and FEA of bone temperature during drilling using a slotted K-wire (Fig. 2(c)) showed the thrust force and torque can be reduced by 30–40% if debris could be evacuated from slots at the K-wire tip [8]. Belmont et al. [9] studied the effects of micro grooves along the K-wire tip (Fig. 2(c) to (e)) and found that the parallel groove (Fig. 2(c)) was the most effective and could decrease the thrust force by 13%. Studies by Tai et al. [8] and Belmont et al. [9] both indicated that grooves parallel to the K-wire axis are more effective at reducing the bone temperature during drilling and have inspired the creation of a new K-wire tip design with notches parallel to the K-wire axis. Adding a notch at the tip also helps to maintain the critical function of the K-wire to fix bone segments. The goal of this study was to investigate the performance of this notched K-wire design to lower the bone cutting force and temperature.

In this paper, a notched K-wire design and the manufacturing procedure using a micro disk cutter are first presented. The preparation of bone samples and the experimental setup for bone drilling tests are then explained. Results relating the temperature, thrust force and torque using regular and notched K-wires during bone drilling are then discussed.

2. Notched K-wire design and manufacturing

2.1. Notched K-wire design

A trocar K-wire with three bevel planes and a bevel angle of φ is selected as the baseline geometry of this study. The notch is machined using a micro-saw on the bevel plane at the tip of K-wire,

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