THERMO-MECHANICAL MEASUREMENTS OF BONE CUTTING: Implications for Thermal Necrosis

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INTRODUCTION

Temperature elevation in the human first metatarsal bone during bunion surgery can lead to irreversible damage to the organic matrix of the bone. As the bone is cut, a large amount of heat is generated within the bone. This temperature response can have adverse effects on the ability of the bone to heal itself. Hippocrates was one of the first to recognize this disadvantage in using power tools to cut bone when he recommended to drill slowly, to remove the tool frequently, and plunge it in cold water to cool the tool and prevent the bone from heating.[1] More recently, microscopic evaluation of bone during and after heat application has shown that a pathology, known as thermal necrosis, can occur when bone is exposed to threshold temperatures.[2] Bonfield and Li concluded that temperatures of over 50°C (122°F) are associated with irreversible changes in the structural and physical properties of bone.[3] This is a considerably lower temperature than 56°C (132.8 °F), which previously had been considered the fatal temperature for bone tissue.[4,5] Eriksson's vital-microscopic study in the rabbit has shown that bone regeneration may be significantly impaired when bone is exposed to a temperature of 47°C (116.6°F)for one minute, proving that thermal damage to bone is the combined result of the temperature and the length of time the bone tissue is exposed to the elevated temperature.[6] The effect of high amounts of heat on the bone for even a short period of time can result in the denaturation of the enzymatic and membrane proteins; bone cells will be resorbed and replaced by fat cells.[7] Surprisingly at a temperature of 44°C (111.2°F)for one minute no significantly adverse effect on the initial bone formation rate was observed.[4]

It is our intent to delineate the heat generation and resulting temperature field in the vicinity of the first metatarsal bone during bunion surgery. Of particular interest is the potential for thermal (avascular) necrosis. Measurements were made using an instrumented cadaver bone to identify the mechanical conditions under which a critical temperature would arise in the surrounding bone and thermal necrosis would begin.

MATERIALS AND METHODS

Thermocouples

The temperature measurements were performed using K-type chromel-alumel thermocouples with a sheath diameter, $d = 0.508$ mm, temperature measuring range of -270 to 1372°C (-454 to 2501.6°F), approximate sensitivity of 0.039 mV/C, and accuracy of ±0.2°C (Omega Engineering, Stamford, CT). This type of thermocouple was chosen because it is reasonably corrosion-resistant and a relatively linear output could be assumed. The thermocouples were calibrated using an ice bath, $T = 0$°C (32°F) as the "cold" reference junction. The relative voltage due to the temperature rise at the thermocouple's hot junction, a bath of a known temperature, was amplified and recorded on a voltmeter (Omega Engineering). We were able to deduce calibration constants and a linear equation to allow us to convert voltage to temperature.

Data Acquisition

The thermocouple data was acquired using a standard PC-based acquisition system. The DT750T screw terminal board was used in conjunction with the DT3003 board (Data Translation, Marlboro, MA) to collect the data. Eight analog channels were converted into four differential inputs and converted to temperature readings in degrees Celsius.

Mechanical Arrangement

Cadaver bones, obtained from the Podiatry Institute (Tucker, GA), were used in order to preserve human bone properties and morphology. Using Steinman pins and an AMSCO /Hall air-driven drill, holes of diameter, d = 0.020mm, were drilled into the bones to house the thermocouples. A thermally conductive paste was injected into the holes prior to thermocouple insertion to bridge the gap between the bone and the thermocouple. Given its high thermal conductivity, the change in temperature through the paste is negligable. Care was taken to avoid the entrapment of air in the hole. Four thermocouples were then embedded into the bone at depths of 1.0mm, 2.0mm, 2.0mm, 1.0mm, respectively.(Fig. 1) We chose a region of measurement corresponding to the area of most pronounced cutting depth, which we postulated should give the highest temperatures. The arrangement of the thermocouples in the bone must ensure that during the osteotomy the tips of the sensors lie in an array around the bone cut; this allows temperature increases at different depths to be recorded.

Temperature Measurements

All osteotomies were performed by Dr. Stephan LaPointe, a podiatrist experienced in bunion surgery, to maintain consistency of pressure. The actual cutting technique was a gentle, controlled motion. Bone cuts were successfully done using a pneumatic oscillating Hall Surgical/Micro100 sagittal saw, provided by Linvatec Corporation. Dr. LaPointe executed an Austin cut as well as a base-wedge cut. The nitrogen tank was obtained from Merriam-Graves, Colchester, VT; the dual nitrogen regulator from Linvatec Corporation.

RESULTS

In the experiments presented, temperature elevations during a simulated osteotomy were measured and recorded. The human cadaver first metatarsal bones were removed from the freezer fifteen hours before the experiment. Their initial temperature at the time of cutting was approximately 15°C (59 °F). Each cutting procedure was performed in one session without interruption.

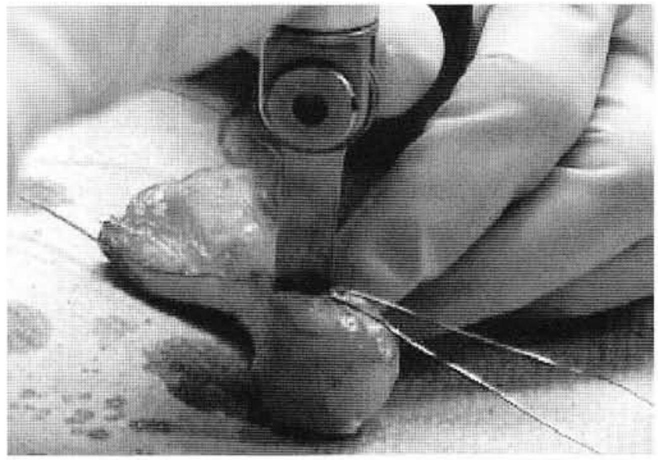

Figure 1A. Cadaveric first metatarsal specimen with thermocouple in place and execution of the osteotomy cuts of the saw.

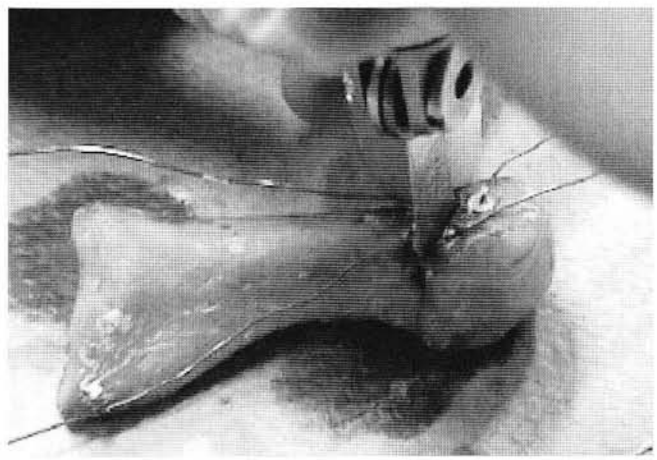

Figure 1B.

First Cut

The temperatures generated during the first cut are shown in Table 1. It should be noted that during this bone cut, the thermocouple located in position #1 was not anchored properly into the bone. Therefore, as the bone saw neared the thermocouple, it became loosened and eventually lost full contact with the bone. Thermocouples #2 and #3 were placed near the tip of the metatarsal bone, relatively far from the initial cutting site, but at a deeper depth. Both of these thermocouples show a small increase in temperature, 20°C (68°F) and 18°C (64.4°F) respectively. Thermocouple #4 was located nearer to the cutting site but at a depth of only 1.0mm. The temperature elevation recorded by this thermocouple was the greatest, reaching a temperature of nearly 37°C (98.6°F). Cutting time was approximately 15 seconds.

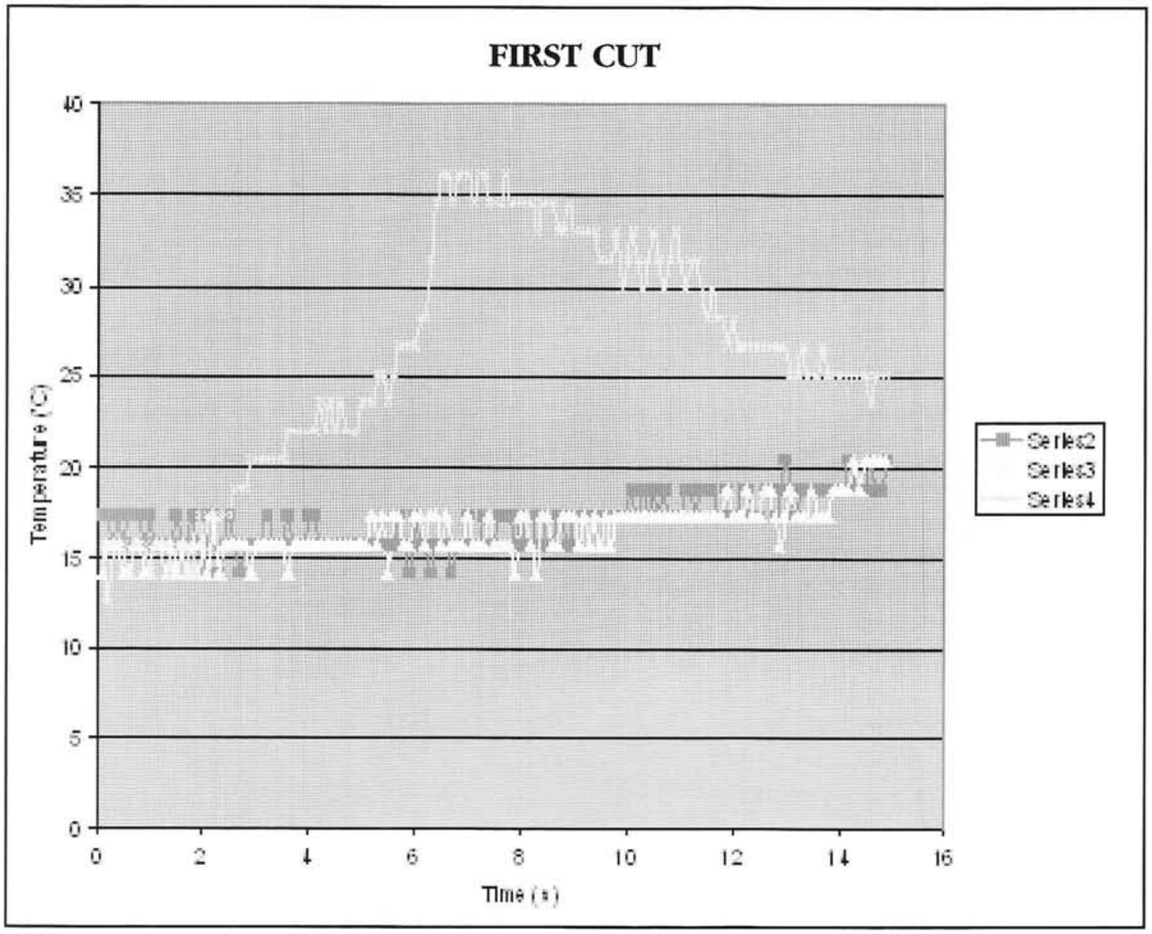

Table 1.

Second Cut

The temperatures generated during the second cut are shown in Table 2. The highest local temperatures were generated in the thermocouples closest to the location of the cut. Temperature recordings at these locations were near 30°C (86°F) and 22°C (71.6°F) respectively. Thermocouples #2 and #3 were embedded into the side of the bone and also show an increase in temperature to approximately 17°C (62.6°F) and 20°C (68°F) respectively. Cutting time was approximately 9 seconds. It should be noted that in both instances, the temperature in the surrounding bone tissue rose at approximately the same rate. When cutting ceased the temperature fell abruptly to the initial temperature.

DISCUSSION AND FUTURE WORK

Because the quantity of heat produced with pneumatic surgical instruments in bone depends on various factors-force, intermittent pressure, location of cut, use of irrigation, surface dimension of the instrument-this study is far from ending.[8] Of primary importance, we intend to identify the mechanical conditions under which thermal necrosis begins.

Force

Using the same operator allowed us to assume a certain amount of consistency in the technique of bone cutting, however, we were unable to measure the changing force that was applied. Therefore, we plan to integrate an apparatus (Instrumentation and Modeling Facility, Burlington, VT) that will allow us to apply a constant vertical force on the saw blade using a basic pulley system.(Fig. 2) The cutting instrument, an AMSCO/Hall pneumatic reciprocating saw, will be clamped to the jig and the bone raised into the blade at a constant force. We will then be able to correlate the thermal measurements with the force application. This data will be used to generate three-dimensional maps of the time-varying temperature field in the cadaver bone as a function of the applied loading.

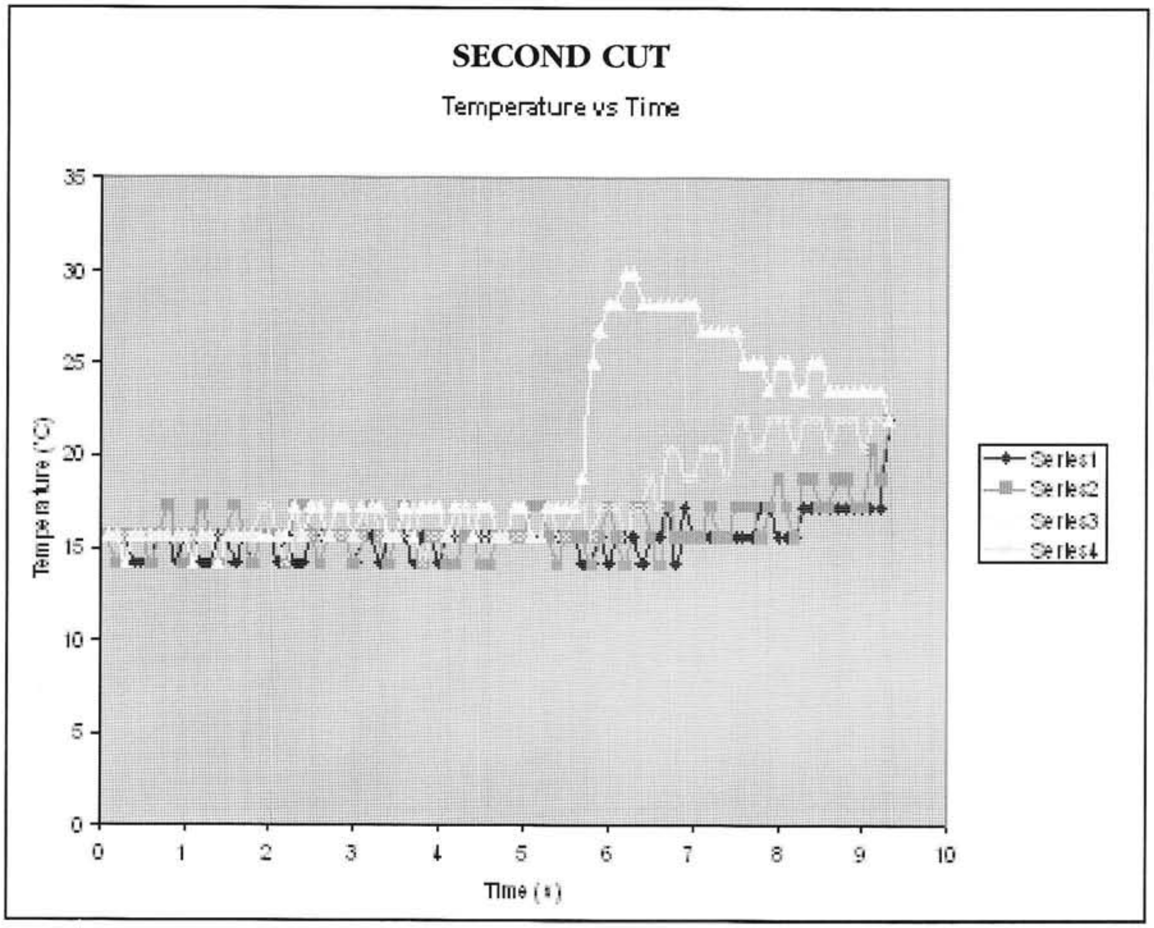

Table 2.

Intermittent Pressure with Irrigation

When steady pressure is applied, the kinetic energy from the power driven saw is constantly being transformed to thermal energy which can cause the local temperature to rise to higher elevations in the adjacent bone tissue. Likewise, studies have shown that the use of a saline without the application of an intermittent load does not lower the maximum temperature because the cooling liquid is unable to reach the furthest depth of the bone cut.[9,10] We therefore intend to investigate this maximum temperature generated as intermittent pressure is applied along with irrigation. It can be concluded that the temperature measured by a thermocouple fixed to the tip of the saw blade represents the actual temperature at the location of the cut. By fixing a thermocouple to the saw blade and polishing it smooth, we can measure the varying temperature as the actual saw travels in and out of the bone.

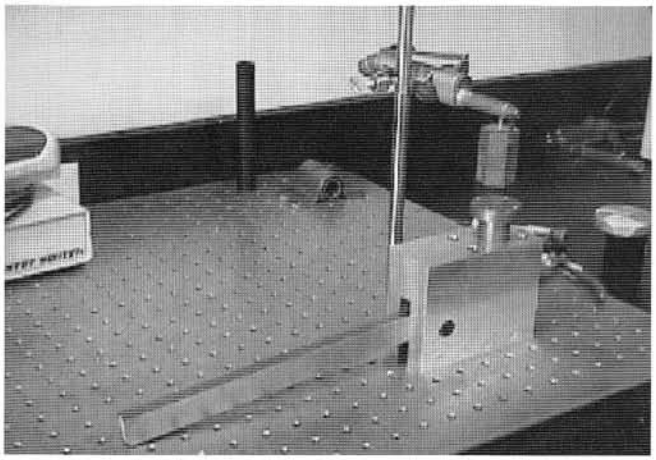

Figure 2. The experimental rig being designed to produce a uniform normal force to the bone during the cutting procedure.

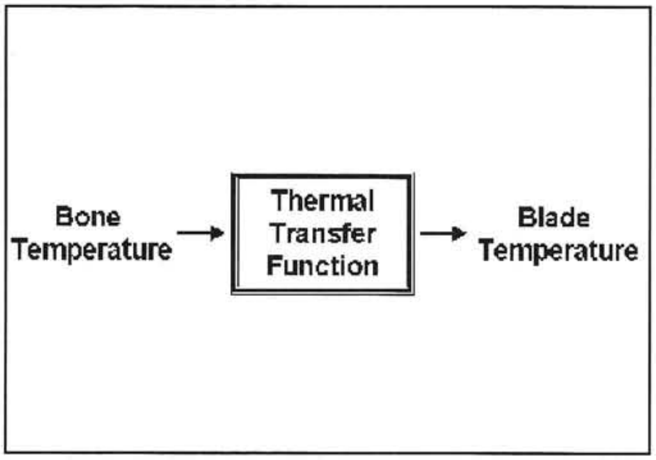

Figure 3. Schematic diagram of the thermal transfer function. Knowledge of this function will permit a bone temperature to be deduced directly from the measured blade temperature.

Location of Cut

If the blood vessels that transport nutrients to bone tissue are seriously damaged, one can assume ultimate bone death as a consequence. The main reason for damage to bone tissue during an osteotomy has been ascribed to the frictional heat, although other factors such as mechanical vibration and rearing of blood vessels may well contribute to the bone injury.[11,12] The amount of frictional heat generated depends on the density of bone at the cutting site. One can conclude that because bone has varying densities throughout (e.g. the more vascular architecture of trabecular bone versus that of cortical bone), varying amounts of heat are generated at different osteotomy sites. We intend to investigate these variations on temperature elevation.

We hope to develop an empirical model that directly correlates blade temperature with the maximum temperature reached in the bone. (Fig. 3) This empirical model could permit indirect measuring of the bone temperature field in the operating room on actual patients without direct application or insertion of a specialized instrument or tool in the patient. In cases where the maximum bone temperature is exceeded, our time-dependent temperature data can be used to predict the size and growth of the region of damaged tissue in time. It is possible that the results obtained from future work in this study may suggest a new design for a instrumented saw blade that can continuously monitor the blade temperature. This saw could feature an automatic cut-off switch or alarm which would activate when the critical blade temperature is reached.

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