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Experimental evaluation of laser cutting of bone

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Abstract

In this paper cutting of bone with an Er:YAG laser is described. The thermal effects during cutting and the surface profile obtained are discussed.

Keywords: Bone; Laser; Thermal; Laser cutting; Laser surgery; Surface roughness

1. Introduction

Orthopaedic surgeons usually use a clinical saw or drill for cutting bone. Precise cuts require considerable manual dexterity to ensure that surrounding tissues and nerves are undisturbed. The cutting rate is related to the pressure applied to the saw or drill in contact with the bone tissue.

The cutting tool should be capable of ready manoeuvrability, allowing controlled cutting and avoidance of direct contact with the bone tissue. These characteristics would also make it suited to computer assisted control. One tool that offers potential for this application is the pulsed Er:YAG (erbium yttrium aluminium garnet) laser which is used by dentists to cut dental hard tissues such as enamel and dentine instead of a high-speed dental drill. Researchers have also investigated how this laser ablates bone [1–4]. Control over the cutting speed is achieved through adjustment of the laser pulse energy and duration. Commercially available Er:YAG lasers deliver short laser pulses (250 μs duration) of infrared light via an optical fibre/waveguide to a lightweight handpiece which can be manoeuvred around the target tissue.

The laser pulses ablate the tissue without making physical contact with it. The laser energy is absorbed within a few hundred micrometers of the surface by the mineralized tissue (hydroxyapatite), and, more particularly, by the small amount of water present in the tissue. The water is rapidly heated causing it to vaporize locally, and generate enough pressure to fragment the mineralized tissue and cause these fragments to erupt away from the surface. In addition a water spray is directed from the handpiece to the lased area to cool the tissue [2,5].

As well as cutting bone in a controlled way, the beam delivery handpiece is well suited to manipulation by robotic control. Movement in this way may minimize the demanding level of dexterity required of orthopaedic surgeons and may serve to reduce the risk of damaging surrounding tissue.

Before this laser could be considered for use for precise cutting of bone, two areas of investigation had to be considered.

The first aim was to assess the thermal loading of bone around the lased area. It is imperative that any temperature change should be as small as possible and of brief duration so that surrounding tissue damage is minimized. We investigated the influence of the different pulse energies on tissue temperature. Current bone-cutting methods with different types of saw blades [6,7] can produce significant temperature increases, which causes concern. The second aim was to examine the integrity of the lased bone surface and the effect of laser pulse energies.

2. Apparatus

2.1. Type of laser

For the experiments on bone an Er:YAG laser was used, which generates short laser pulses (250 μs duration) of 2.94 μm wavelength, in the near-infrared region of the electromagnetic spectrum. At that wavelength maximum absorption of the infrared light occurs in water. This facilitates the effective ablation process, which is based on the vaporization of the bone cell's water [8].

The laser pulses were directed by use of a handpiece, which also simultaneously emitted an air-water spray, which assisted in the tissue absorption of the laser radiation and provides cooling [2].

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2.2. Test rig

The laser tools are difficult to hold steady for the duration of its operation. Thus the laser handpiece was fixed above the bone surface. A manually operated translation stage was used to move the specimens linearly across the beam.

3. Experimental procedure

3.1. Temperature

A 4×3 matrix of 1 mm diameter holes 2 mm apart was machined into three bone samples to locate temperature sensing fibre-optic probes.

Each specimen of bone was fixed on the test rig. The laser handpiece was positioned approximately 2 mm above the bone surface and 2 mm from the first thermometer. The second and third thermometers were placed, respectively, 4 and 6 mm from the site to be lased. For each test, 50 pulses (10 pulse/s) of energy ranging from 300 to 1000 mJ were applied to drill holes of approximately 1 mm surface diameter.

3.2. Surface roughness

Incisions varied between 4 and 7 mm in length, width 0.8 mm. This corresponds to an energy density (for a 5 mm track) of 6.25 J/mm^2 for each 100 mJ. For a pulse energy of 300 mJ this would result in an energy density of approximately 18.25 J/ mm^2 rising to 62.5 J/mm^2 for 1000 mJ per pulse.

The distance between sample and laser tip was kept constant by raising the specimen tray after each pass of the laser.

4. Results

4.1. Temperature

Figs. 1 and 2 show the variation of temperature with laser power. In each case, the temperature was recorded below the bone tissue ambient temperature which before experiments was 26.1 °C. The maximum/minimum temperatures for each laser condition are summarised in Table 1.

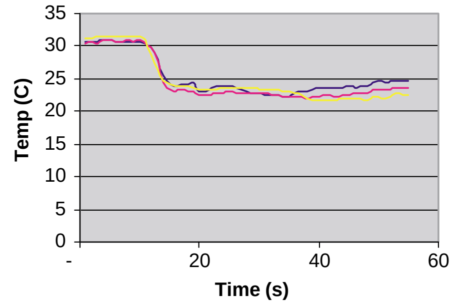

Fig. 1. Temperature variation with time at 300 mJ.

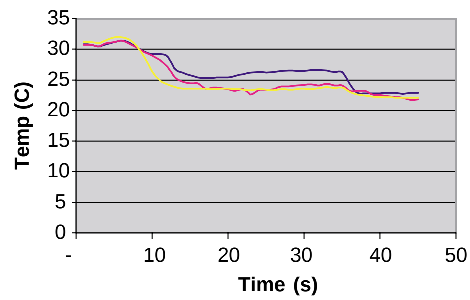

Fig. 2. Temperature variation with time at 400 mJ.

The maximum temperature of 32 °C was recorded at the highest energy of 1000 mJ per pulse.

4.2. Surface profile

4.2.1. Comparison of a free hand and a stable rig test

The surfaces of the lased bone specimens were examined using a high-powered optical scanner (ZYGO) that utilizes scanning white-light interferometry to capture a detailed three-dimensional image.

The optical scanner requires the sample surface to be reflective. While bone is light in colour it is not sufficiently

Table 1
Probe temperatures

Pulse energy (mJ)	Energy density (J/mm^2)	Probe 1 (2 mm)		Probe 2 (4 mm)		Probe 3 (6 mm)	
		Min (°C)	Max (°C)	Min (°C)	Max (°C)	Min (°C)	Max (°C)
300	53.0	24.7	29.6	23.7	28.5	23.0	31.5
300	53.0	23.3	27.6	22.9	26.5	22.6	25.5
300	53.0	22.2	28.1	22.0	27.7	21.6	26.3
400	70.7	22.5	28.8	21.7	27.2	21.8	24.3
400	70.7	22.5	28.9	21.8	28.5	21.7	28.6
600	106.0	25.3	28.0	23.2	26.7	26.9	29.0
600	106.0	25.6	31.2	23.6	27.9	26.4	28.7
800	141.4	24.5	28.4	22.9	25.8	24.3	26.4
800	141.4	28.2	29.9	25.5	26.5	26.3	28.4
1000	176.7	26.8	31.1	23.7	31.1	22.9	32.1

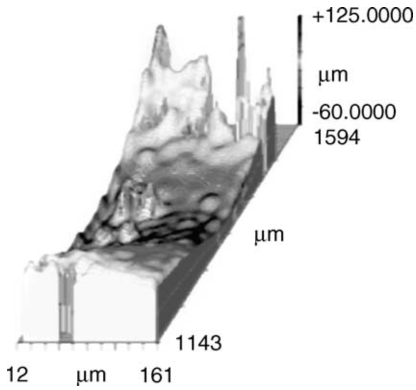

Fig. 3. Base of "free hand" incision.

reflective enough for the ZYGO to perform a rapid scan of the entire incision. Thus only a small area of two characteristic incisions was examined.

The first specimen (Fig. 3) had an incision made with the laser being held by hand, 400 mJ per pulse, at 10 pps, being applied for 250 pulses. The next incision was made with the sample fixed in the test rig, with the hand-operated translation stage used to move the sample in the reciprocating motion described. In this case the laser settings were 600 mJ per pulse, at 10 pps, for 250 pulses (Fig. 4).

The scanner was able to provide data for the base but not the steep walls of the lased incision.

The "free-hand" procedure was less difficult to analyse as the incision was less precise. The wall surface, as well as the base, could therefore be scanned. The surface profile of the top of the bone surface was also taken as a reference.

4.2.2. Comparison of the surface roughness of a normal and lased bone surface

The surface roughness of "normal" and lased bone specimens was compared. The lased incision was made at 500 mJ per pulse at 10 pps for 50 pulses. In Figs. 5 and 6 the normal and the lased bone surface can be seen, respectively. The ZYGO software can directly give the average roughness of the scanned areas (through an estimation of the acquired scan). This results in an average roughness for the unlased bone of 2223 and 2550 nm of the lased bone. Comparing the outcomes the lased bone surface is rougher than the normal one.

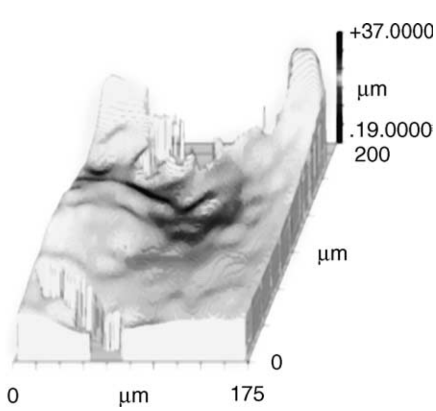

Fig. 4. Base of "fixed" incision.

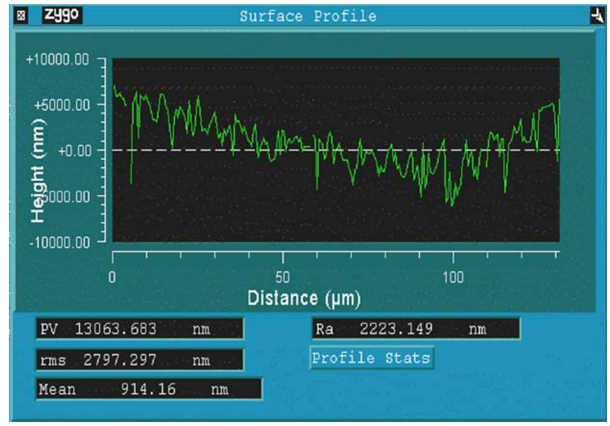

Fig. 5. Normal bone surface.

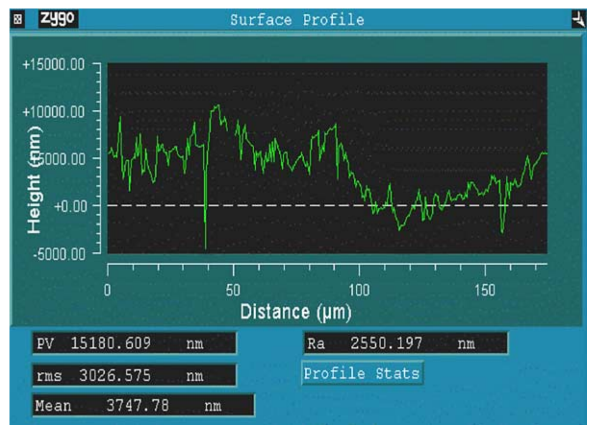

Fig. 6. Lased bone surface.

5. Discussion

Cutting of bone with orthopaedic saw blades normally generates substantial temperature increases [6,7]. Toksvig-Larsen et al. measured temperature rises between 34 and 450 °C using a thermocouple located 2 mm from the saw blade cutting surface. In the present experiments the thermometers were positioned 2 mm away from the lased site, to enable comparison with conventional sawing. With the Er:YAG laser the temperature during irradiation initially dropped. During the 20 s of irradiation there was a maximum rise of 6 °C with pulse energy of 1000 mJ. These preliminary laser tests confirm the effectiveness of the water spray in keeping the tissue temperature close to ambient.

The temperature closer to the lased tissue would have been higher than that recorded. These specific thermometers used could not be located closer to the lased area without risk of their direct exposure to the laser beam.

The surface profile data for the specimens tested indicated that the lased surface is rougher than that of the original bone. Further tests are needed to compare these data with those for bone cut with a saw blade in order to discern whether lasing adversely affects the tissue. If the roughness of the surface is unacceptable low energy pulses could be used to reduce the extent of these effects on the surface.

6. Conclusion

Despite reports on the clinical use of the Er:YAG laser for cutting bone there remains a lack of evidence to determine the level of laser pulse energy that can be used without adverse heating of the underlying tissue. This study has addressed this concern by use of controlled experimental apparatus. Further work is needed to better evaluate the integrity of the lased surface, in order to ensure the subsequent bone healing is not affected.

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