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Laser repair of liver

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ABSTRACT

Laser repair of liver using albumin is a promising method for treating liver trauma. Concentrated human serum albumin is applied to a liver laceration and then denatured using a laser. These repairs were pulled with a material tester to measure the ultimate strength of the laser repair. We show that the ultimate strength of the liver repairs tends to increase with delivered laser energy, that the mode of delivery (pulsed versus continuous) does not matter, that the repair strength correlates with the area of denatured albumin, and that strong welds cause about 1.5 mm of thermal damage.

Keywords: welding, thermal damage

1. INTRODUCTION

Our laboratory has recently begun using laser welding techniques on solid tissues that are notoriously difficult to repair with sutures (liver and spleen). We have achieved rapid hemostasis (in swine in vivo) of lacerations (10 cm long and 1 cm deep) and lobar resections (5×2 cm). All repairs healed without complication.

Laser welding is achieved by spreading albumin dyed with indocyanine green over the site to be repaired. An 800 nm diode laser irradiates the albumin solder and causes the albumin to denature and create a water-tight bond. Our experience has shown that laser welding strengths tend to increase with increasing delivered laser energy. Since thermal damage to the liver also increases with laser energy, we were particularly curious how repair strengths correlated with thermal damage sustained by the liver.

2. MATERIALS AND METHODS

Human serum albumin (25%) was obtained from the pharmacy and concentrated in an Amicon 8400 ultrafiltration cell until an albumin concentration of 54% was reached. A small volume of a highly concentrated solution of indocyanine green was added to the 54% albumin to create solder with an absorption coefficient $\mu_a = 50\,\mathrm{cm}^{-1}$ and an albumin concentration of 53%.

All liver was obtained from the supermarket. The porcine liver was cut into strips approximately 8 cm long, 2.5 cm wide, and 1 cm thick using a scalpel. Liver was used immediately after purchase, so storage was unnecessary. The liver pieces were cut into two sections across their width. The edges were proximated by hand. A thin layer of albumin solder was spread (on the native external surface of the liver) over the junction of the liver and circular spots were denatured with the laser.

All welding experiments were conducted with a Coherent diode laser with a peak emission at 806 nm. The light was coupled into an 800 μm fiber. The distal end of the fiber had a collimating lens that produced a uniform (±25% of the mean) circular spot. The fiber was positioned 20 mm above the sample to repeatably deliver spot sizes of 6 mm in diameter. The laser was operated in continuous wave mode or in pulsed mode with 100 ms laser pulses at 5 Hz.

The three delivery irradiation patterns used three, six, or nine spots, all 6 mm in diameter (figure 1). Welds were performed by irradiating at constant power for different time periods for continuous wave welds, and for different numbers of pulses for pulsed welds. The number of pulses and irradiation times were chosen such that each continuous wave weld correlated with a pulsed weld that received an equal total amount of energy per unit area (i.e., radiant exposure).

The welded samples were then placed into our state-of-the-art binder clip liver holders and pulled on the Chatillon Material Tester with a 500 g load cell (Figure 2). This figure shows the typical failure mode in which the coagulated

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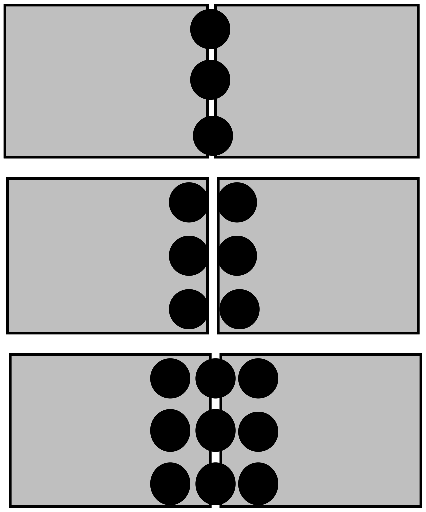

Figure 1. Distribution of welding spots for the liver welding experiments. Liver strips 25 mm wide are transected in the center and then rejoined by coating with albumin. The albumin is denatured using different laser spot patterns. The laser spots were 6 mm in diameter and there was not a gap between the pieces of liver during welding.

albumin pulled off the liver surface. The strongest welds were associated with the weld failing by pulling the coagulated albumin apart. The pull speed was 1 mm/s. The stress was calculated by dividing the force at ultimate failure by the total area of the liver covered by denatured albumin. The strain was based on the initial length of the liver sample after loading in the materials tester (typically 2.5 cm).

After being pulled, the liver was sectioned and examined under a microscope, and the depth of thermal damage was measured and recorded. The onset of thermal damage was simply delineated by a change in the color of the liver.

3. RESULTS

Figure 3 shows the stress-strain relationship for a typical mechanical pull test. This shows that for the liver sample, the stress increases nearly linearly with the stain, up to the point where the weld fails. The large strain of 0.5 is a property of the liver and not of the denatured albumin in the weld. The denatured albumin is much stiffer and will fail at much smaller strains.

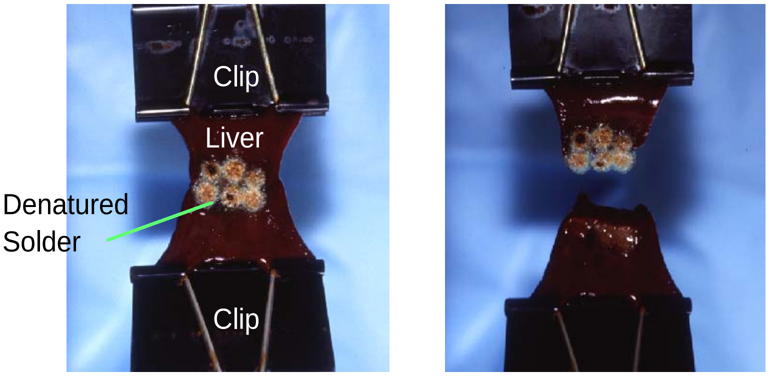

Figure 2. Laser welded liver sections with six spots mounted in the mechanical tester. Binder clips were a simple, inexpensive way to attach liver to the tester.

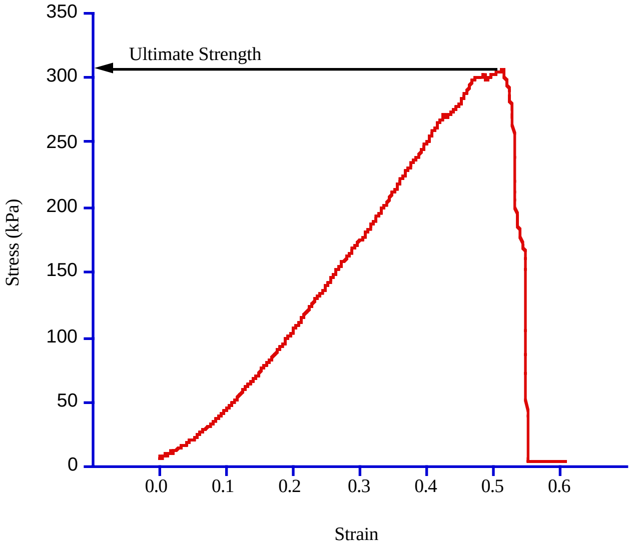

Figure 3. Stress-strain response of welded liver section. Ultimate strength of the weld defined as the maximum stress before the weld fails.

As shown in Figure 4, the weld strengths for six spots increased as the total delivered energy was increased up to 163 J/cm^2. However, the increase in the weld strengths for 122 J/cm^2 and 163 J/cm^2 was minimal. The highest radiant exposure (163 J/cm^2) was near the threshold for burning or charring the albumin. The delivery method (pulsed versus continuous) did not make a significant difference in the final strength of the liver repair.

The continuous wave weld strengths displayed in Figure 4 were irradiated for 3.3 seconds for 25, 37, and 50 W/cm^2 at each of six spots. The pulsed welds displayed in Figure 5 used 25 pulses at necessary energies to provide equal total energy delivered. Each experiment was repeated five times for both pulsed and continuous wave delivery and for three, six, and nine spots.

Figure 5 shows results for welds using 163 J/cm^2 and three, six, and nine spots. The ultimate strengths were systematically stronger for pulsed welds than for welds made with continuous wave irradiation. However, the error bars are sufficiently large that these differences are not significant. Not surprisingly the ultimate strength was effectively constant with increasing area (number of spots). This confirms the experimental observation that the mechanism of failure is that the denatured albumin pulls away from the liver.

Figure 6 shows the weld strength as a function of thermal damage for welds made with six spots. The radiant exposure for each data point is omitted for clarity, but greater ultimate strengths are associated with greater radiant exposures. The error bars denote the standard error of the mean of five samples.

4. DISCUSSION

Weld failure resulted because either the denatured solder pulled away from the liver or the denatured solder broke in the middle. In a few rare cases, the liver itself began to rip before the solder broke. The strongest welds corresponded to when the solder broke; these were typically associated with the highest radiant exposures. Weld strengths for six spot delivery increased as the total delivered radiant exposure was increased up to 163 J/cm^2 (Figure 4). We expected that the highest radiant exposures would show a slight decrease in repair strength due to underlying tissue damage. We did not observe a decrease at the highest radiant exposures used in this experiment, and in other experiments, the ultimate strength did not decrease significantly even when significant charring of the albumin was present.

For equal amounts of delivered energy, the pulsed laser welds were usually stronger for all weld configurations, and had equal thermal damage to the continuous wave welds. However, the differences in strength were small and

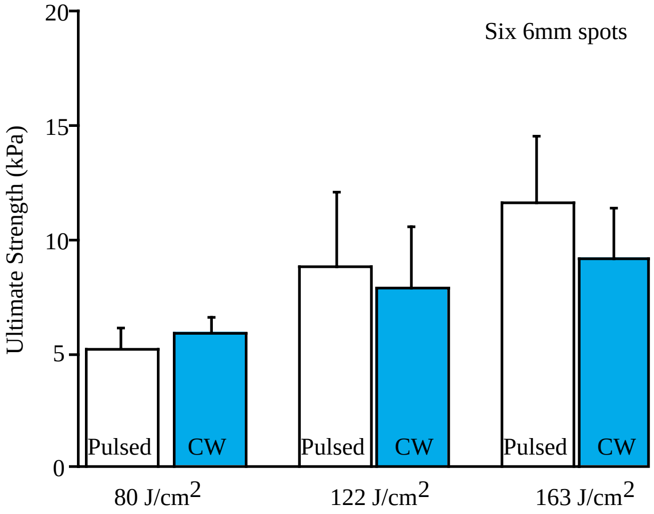

Figure 4. The weld strengths for liver incisions repaired using albumin and six laser spots. Three different total delivered radiant exposures were tested 80, 122, and 163 J/cm^2. There was not a significant difference in the strengths between continuous wave or pulsed irradiation light delivery. The "CW" denotes welds using continous laser irradiation and pulsed indicates 5 Hz laser pulsing.

the variation sufficiently large that this effect is probably not statistically significant. In other words, pulsed and continuous welding are equally effective, with the added clinical benefit that the laser energy can be delivered in half the time for continous irradiation compared to pulsed irradiation. That said, the most successful repairs were achieved using 100 ms pulses at a 5 Hz repetition rate for a total of 25 pulses at 6.6 J/cm^2 per pulse (i.e., 46 J/spot) in the six spot configuration. While similar, if not slightly superior, strengths were achieved with the nine spot configuration, these welds produced roughly 50% more thermal damage (not shown). This increase in damage, combined with the ultimate strength data, suggests that the two row (six spot) delivery pattern may be optimal for repairing lacerations in liver.

Figure 5 shows essentially constant ultimate strength for different welded areas. This shows that stronger repairs can be created by welding larger and larger areas. Alternatively, the primary failure mechanism is not albumin fracture, but rather release or tearing of the denatured albumin away from the liver surface. Consequently, the most appropriate area for calculating ultimate strength is the surface area and not the cross sectional area of the albumin.

The 1.5 mm zone of thermal damage created during liver repair may seem excessive. However, achieving hepatic hemostasis with argon beam coagulation creates 5–10 mm of thermal damage. Conventional suturing techniques to stop bleeding in the liver create similar zones of necrotic tissue. The 1.5 mm of thermal damage is negligible when compared to these other technologies. Furthermore the liver has an extraordinary capacity to regenerate itself. One only needs to stop bleeding and bile leakage so that the liver gets a chance to repair itself.

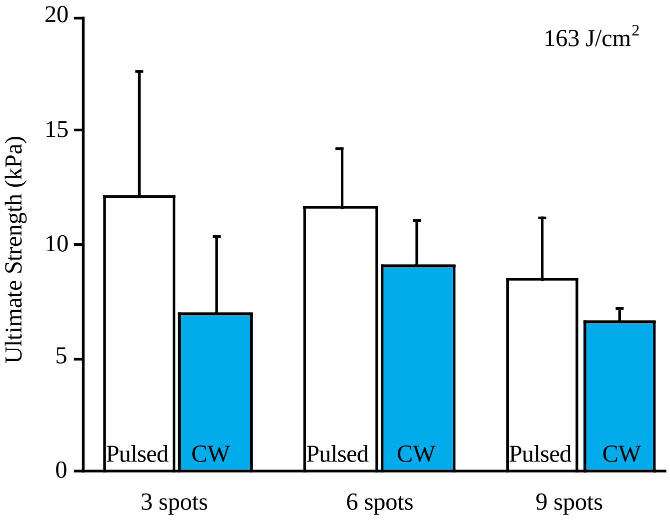

Figure 5. The weld strengths for liver incisions repaired using albumin and three, six, and nine laser spots. Each repair received the same radiant exposure — 163 J/cm^2. The "CW" denotes welds using continous laser irradiation and pulsed indicates 5 Hz laser pulsing.

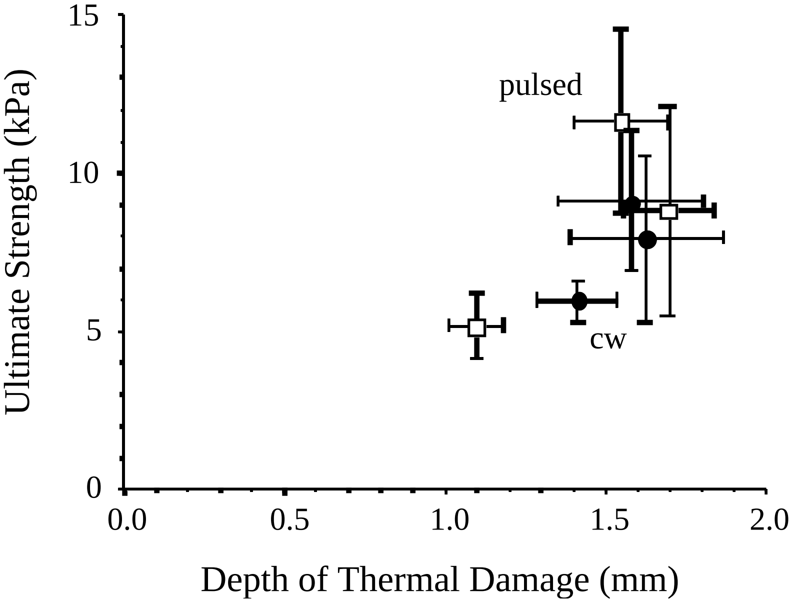

Figure 6. Weld strengths for six spots plotted against measured thermal damage for pulsed and continuous ("cw") laser irradiation. The three data points in each series represent the average and standard deviation for each of the three radiant exposures. The empty squares represent pulsed laser irradiation and the filled circles are for continuous laser irradiation.