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EXPERIMENTS**

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Laser Welding of Bone: Successful *in vitro* Experiments

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ABSTRACT

A method for "welding" bones is being developed. Tensile joint strengths of chicken bones welded *in vitro* have exceeded one kilogram. Welding was performed with either a Nd:YAG (1064 nm) or a diode laser (820 nm). Light was delivered with an optical fiber held a few millimeters from the bone surface. A solder was developed to assist in the welding process.

1. INTRODUCTION AND MOTIVATION

Laser techniques for welding soft tissue have been in development for three decades. The concept is to utilize a laser to heat the tissue at the site of a surgical closure just enough to break the tertiary structure of bonding proteins (namely type I collagen) without serious chemical damage.¹ Welding of hard tissues is even more challenging than the welding of soft tissues. The mineral component has far different thermal properties than type I collagen and may hinder the welding mechanism. To our knowledge no successful laser welding of bone has been reported to date. Our current approach is to chemically remove the mineral matrix from a thin layer of the joint surface, then use either a diode laser or a Nd:YAG to heat the joint.

The motivation for hard tissue welding is to not only improve current orthopedic techniques, but to allow accurate fixation of bone fragments where there is no current capability. Direct approximation is not currently possible in very small bones, or when the bone fracture is within a joint. Extrapolation from soft tissue welding suggests that another advantage of hard tissue welding may be decreased healing times.²

2. METHODS

Diaphysial segments of chicken tibia were prepared by removal of muscle tendon, epiphysial ends and periosteum. The procedure for cutting the chicken bones and preparing the joint ends was designed specifically to generate reproducible joints for comparison of method variations. Two slightly different cutting methods were used. In method A, a thick bladed saw was used to cut the bones; and in method B

are thinner bladed saw was used. The bone ends to be welded were sanded with wet 400 grit paper in order to remove burrs or saw marks which might prevent intimate contact of the bone ends. More sanding was required for bones cut by method A than by method B. The bone ends were then placed in a solution of (approx. 5N) HCl for 5 sec and set on the untreated ends for 60 seconds in order to decalcify the bone ends and expose collagen.

A Nd:YAG laser (1064 nm) and a diode laser (820 nm) were tested separately for welding efficacy. Bones cut with method A were held in a clamp with approximately 4 kg of compression force applied. Bones cut by method B were held in a C clamp with roughly 2 in-lb of torque applied. An optical fiber was used to apply the laser radiation to the bone surface. In the case of the Nd:YAG a 400- μ m fiber was used; for the diode laser a 600- μ m fiber was used. The wattage out of the fiber was in the range 3-5 W for both lasers. The general technique was to irradiate the joint edge from a couple of millimeters away until the bone showed indications of carbonization (about 10 s). The irradiating fiber was then moved to a position a millimeter or two away along the joint edge and the process was repeated.

Fig. 1. Schematic of the bone preparation procedure, laser welding procedure and the joint strength measurements.

After welding, the bones were placed in saline solution for several hours, to insure that they were rehydrated. The joint strength was then measured. One end of the bone segment was attached to a force gauge while the other end was pulled until the joint separated. The peak tension was recorded.

3. RESULTS

3.1 Nd:YAG welding results

Nine bones were cut by method A, and welded with the Nd:YAG laser as described above. The mean joint strength was 603 gm. The maximum joint strength was 865 gm, while the minimum joint strength was 149 gm. Several attempts were also made to weld bones with little or no carbonization. In general, these bone joints had significantly less strength.

Bones cut by method B gave slightly better results. Of nine bones the average joint strength was 684 gm. The maximum joint strength was 1600 gm, and the minimum was 220 gm.

3.2 Diode laser welding results

For welding with the diode laser at 820 nm a "solder" incorporating indocyanine green (ICG) was used to enhance absorption at the diode wavelength preferentially at the joint. ICG has a broad absorption band peaking at roughly 804 nm. At 820 nm the absorption is roughly half its peak height. Dye enhancement of the solder used in soft tissue welding has been shown to improve selective localization of heat, resulting in less damage to surrounding tissue.^{3,4} Following this lead, a "solder" consisting of water, albumin and ICG with the thickness of a paste was used. These pastes were applied to the bone surfaces to be welded after the acid treatment. Preliminary results show that thicker pastes result in stronger welds.

The welding technique was altered slightly from that used with the Nd:YAG laser. Rather than radiating directly on the bone junction, laser light was applied either slightly above or slightly below the junction with the intent that the light would penetrate deeper into the bone and be absorbed in the junction.

Only bones cut by method A were welded with the diode laser. The average joint strength of 13 bones was 420 gm. The maximum joint strength was 1002 gm and the minimum was 185 gm. A wide variety of paste thicknesses were used with these bones. A weak correlation was found between paste thickness and strength. The thicker the paste the stronger the weld.

3.3 Controls

To determine the effects of the acid alone without laser radiation, several bones were prepared and placed in a clamp for an amount of time similar to that required for welding. Three bones were cut by method A and all were found to have zero joint strength. One of these bones was prepared with only acid treatment and no solder, one was prepared with acid treatment and ICG in the junction and one was prepared with acid treatment and a paste of ICG, water and albumin in the bone junction.

Four bones were cut by method B and prepared as controls with acid treatment only. Three of these bones had a joint strength of 360 to 400 gm while the fourth had zero joint strength.

4.0 DISCUSSION

Joint strengths of over one kilogram have been achieved in chicken tibias welded with a laser. These preliminary results do not show a clear advantage to using the diode laser in combination with a "solder" including ICG versus using a Nd:YAG laser. With identical bone preparation procedures, bones welded with a diode laser had lower average joint strengths, although the maximum joint strength obtained with the diode laser was greater.

The methods used for preparing and holding the bones for welding was designed to be easily reproducible, so that different methods of laser welding could be compared. Two different methods were used and it was found that the joint strength depends on the preparation method.

Several attempts were made to weld bones, by turning off the laser radiation just as the bone began to carbonize on the surface. Bones welded in this manner had significantly less strength than bones welded in a more aggressive manner. This indicates that the heating which results in carbonization is an integral ingredient for obtaining a strong weld and that the mechanism may not be simple collagen bonding as has been presumed in soft tissue welding. In addition, the weld strengths obtained are significantly greater than those which have been achieved in soft tissue collagen welds.^{5,6} The surface area of bone joints welded was on the order of 0.5 cm, leading to joint strengths on the order of 1400 gm/cm², which is significantly greater than the 160 gm/cm² tensile strength reported by Bass et al. for rat tail tendon.

The results presented here are very preliminary, an extensive, methodical approach must be used to determine the potential of the wide variety of welding techniques. Future plans include varying the laser irradiation parameters as well as the methods of bone preparation, and examining the welds with an electron microscope.

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