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SKIN SUTURE MODELING USING LASER WELDING

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Abstract. *The skin suture process is used to repair and restore the form and function of the tissue after surgery. In general, special needles, surgical sutures and staples are used. Despite the advanced materials used for suture, some non-uniformity may occur in the healing process, which may cause infection and tissue damage. For this reason, health professionals seek alternatives to solve this problem. The use of laser tissue welding, in which heat sources are used, may be a promising and interesting technique. Laser welding provides advantages, when compared with conventional techniques, offers an immediate watertight closure of the incision, reduced foreign-body reaction and operation times, as well as better cosmetic appearance. When performed under controlled conditions, no tissue trauma occurs. However, due to the large number of variables, the mechanisms that act on the laser welding are not yet completely understood. It is known that laser welding is a phenomenon which is thermally-dependent on the tissue laser energy absorption. Biothermomechanical alterations are the basis of the tissue bonding in this process. Thus, the purpose of this study is to evaluate the skin welding process by using a laser source. An in vitro study has been proposed by using pig skin to evaluate the thermal gradient, the visual appearance and bond strength under the influence of external pressure, laser power and material addition. In the present study, the bond strength of the samples was evaluated by tensile tests. Simultaneously, was proposed a mathematical model to estimate the thermal effects on the skins by using techniques of similitude in engeneering and considering parameters such as exposure time and laser power and measurement position. An in vivo mathematical model for in vitro study proposed to determine the thermal gradient and stress distribution in skin under the laser was also adapted. The studies showed that the incisions can be closed by a laser source using solder, being that, for samples in vitro, the pressure applied to bond the incision has little influence. The thermal gradients are important for the union of the tissues, such that low levels of temperature, below 40 ° C has little influence and temperatures above 60 ° C could cause tissue damage.*

Keywords: *laser tissue welding, biothermomechanical , similitude, skin suture.*

1. INTRODUCTION

Surgical procedures with closure of wound records date back to times of mummies using leather (SOUZA, FAGUNDES, et al., 2001). Over time, alternatives to improve the protocols of treatment of wounds have emerged. In this case, the surgeon must perform the wound closure in order to restore the tissue form and function with a suitable method. With the advances in surgical techniques, there has been a need to minimize the period of treatment, as well as reduce the postoperative complications related to impaired tissue synthesis. Several researches are being developed to improve the closure technique, either by synthetic suture, staplers and more recently with alternative methods such as adhesives and "tissue welding".

The most widely used procedure for wound closure is the conventional suture closure. This mechanism uses specific needles and wires. Despite being a widespread technique, it brings some disadvantages, such as trauma to the tissue caused by needles and a non-uniform closure. It should be emphasized that the suture materials are foreign bodies which can cause inflammatory reactions. Additionally, sutures do not create a watertight seal.

The tissue "welding" is being studied as an alternative to conventional suture. The joining of tissue can be achieved by the application of heat through several sources such as electrical resistence, ultrasound and laser. However, tissue welding is unlikely to replace conventional suture in all aplications.

Welding as alternative form of tissue closure has proven quite efficient showing several advantages compared to conventional suturing techniques, as reduced operation time, reduced trauma, immediate witertight tissue closure, elimination of foreing body reaction etc (POPPAS; SCHLOSSBERG, 1994; TALMOR; POPPAS; BLEUSTEIN, 2001).

However, these alternative techniques of tissue closure also have some disadvantages such as low strength, thermal damage to the tissue by heat transfer, technical and operational difficulty, poor reproducibility as well as the mechanism of tissue welding is not understood (SCHERR; POPPAS, 1998; TALMOR; POPPAS; BLEUSTEIN, 2001; MCNALLY, et al., 1999).

In addition, the degree of success of all new surgical techniques must be judged in comparison with existing techniques. As regards tissue welding, according to the literature, there is somehow consensus that the laser as a source of energy provides several advantages in relation to conventional suture (FRIED; WALSH, 2000; MCNALLY, et al., 1999; FORBES, 2009).

The present work studied the skin welding process using laser as an energy source. The study was performed through an experimental approach and mathematical models. Analysis *in vitro* using samples of pig skin in order to evaluate the influence of laser output power, applied pressure between the two edges of the incision and the use of solders was done. We studied the thermal effects, visual aspect of the closure and tensile strenght of tissue through tests of traction on skin samples subjected to the process of laser welding and conventional suture.

A mathematical model *in vivo* was adapted for *in vitro* studies. There was also a proposal of a new mathematical model using experimental data developed as a reference at work. This model was developed using similitude and aimed to evaluate the temperature variation of the skin exposed to laser radiation.

2. MECHANISM OF LASER TISSUE WELDING

The interest of researchers and manufacturers in search material with ideal qualities and/or alternative processes is related to syntesis based on surgical procedure.

The conventional methods for tissue repair such as suture, stamples and clips are reliable, cost-effective and suitable for almost any type of tissue. However, due to mechanical trauma (of sutures and staples), the use of these conventional methods causes injury to the tissue. Owing to its nature, the suture or staple, are considered foreign bodies. Tissue injury and foreign-body reaction increase inflammation. In the search for alternative methods, the laser as a source of energy for tissue welding proved to be extremely important and effective in several applications. The use of the laser to induce thermal changes in connective tissue proteins is of particular interest for the joining of severed tissues, where the proteins of the target tissue are coagulated to bond adjacent edges. The degree of success of any new surgical technique must be judged, that is, compared with existing techniques.

The first success with the use of laser in biological tissue welding was in 1979 when Jain and Gorisch repaired incisions made in small blood vessels of rats with Nd:YAG laser(SCHERR; POPPAS, 1998). In a sequence, several studies have been conducted using a variety of lasers for welding of biological tissues.

Although much of the research was inicially performed in vascular anastomosis, experiments, especially using laser tissue welding, have been performed in most specialties. Tissue welding has been successfully used to repair nerves (MENOVSKY; BEEK; VAN GEMERT, 1996), porcine arteries and veins (OTT et al., 2001), bovine aorta (MCNALLY et al., 1999), femoral vein of dog (SMALL, et al., 1998; WHITE, et al., 1986), skin (GULSOY, et al., 2006; TABAKOGLU; GÜLSOY, 2010), among others.

Several laser systems have been used successfully for joining tissue, since the argon laser (λ = 488-514 nm) up to the CO_2 laser (λ = 10.6 μm). However, the choice of laser system and the parameters used for welding are based on empirical information, as well as the welding mechanism that is not well understood (BRODIE, 2003).

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Despite the possibility of using any energy source, the laser is the most used and has been studied as an alternative method of closure tissue over the last 40 years (FRIED; WALSH, 2000). The progress of laser tissue welding is slow in part due to the large number of parameters involved (MENOVSKY; BEEK; VAN GEMERT, 1996). Besides, the mechanism of tissue welding is not well understood which makes it difficult to set laser parameters for optimal welding and determine when the weld has been reached (BRODIE, 2003). The energy level and exposure time of the laser can be suitable for some situations and specific type of tissue and unsuitable for others (POPPAS; SCHLOSSBERG, 1994).

For the time being, laser welding is unlikely to replace the conventional suture in all applications, but has already achieved a comparable functionality with conventional techniques of tissue closure with the addition of some advantages as described previously (POPPAS; SCHLOSSBERG, 1994; MCNALLY et al., 1999).

Two advances in the application of biological tissues with laser welding have been useful in reducing problems such as termal damange and low strenght.

The addition of endogenous and exogenous materials helps to keep the tissue edges aligned and strengthen the wound, particularly in acute postoperative healing phase period. Useful welding materials include blood, cryoprecipitate (typically plasma), fibrinogen and albumin (TABAKOGLU; GÜLSOY, 2010).

A chromophore is a dye that can be combined with the solder material to absorb selective wavelengths. The application of laser wavelength-specific chromophores provides a differential absorption between the dyed region and the sorrounding tissue (MCNALLY, et al., 1999).

The precise mechanism of laser tissue welding is still unknown. An understanding of both the tissue and the solder proteins involved in the welding and soldering processes as well as the heat induced interactions that occur within them is fundamental to the establishment of their physical bonding mechanism.

Talmor; Poppas; Bleustein (2001) mention that one of the reasons for the difficulty in understanding the mechanism of welding has been the large amount of parameters involved in the process. The laser weld is believed to be primarily a thermal dependente phenomenon. Regardless, the formation of tissue weld is the result of the application of eletromagnetic energy in the form of laser light. The laser light is converted into heat into the tissue, and it is believed that this heat is responsible for tissue structural changes. The tissue is heated as a result of laser energy and this energy induces macromolecular structural alterations which are the basis of the tissue weld. The literture point out that collagen fiber bonding, through some form of interdigitation, fusion or ohter physiochemical means, is the primarily responsable for the welding effect.

Different tissues such as skin and blood vessels are altered so diferente (SCHERR; POPPAS 1998). The biochemical changes that occur in a tissue may not be reproduced in another type of tissue. In addition, different laser systems create a variety of ultrastructural changes that seem to be laser specific.

3. MATERIALS AND METHODS

The experimental analysis was implemented in order to assess the feasibility of laser welding process of tissue (pig skin). In this way we designed a device which enables the pressure on the edges of tissue and at the same time move the laser source in a pre-defined route.

In this first study related to welding of living tissue, the aim is to check the influence of pressure levels, laser output power and addition of solders compared to the conventional process of suture. Soon, the strenght of the union was evaluated by tensile test in skin samples subjected to the laser welding process under the influence of laser power, the inclusion of solders (albumin + "india ink") and pressure on the edges of the incision.Welded samples were analyzed qualitatively on the visual aspect of the union and strenght.

3.1 Design of Pressure Application Device

A device to apply a specific pressure on skin samples was manufactured using structure made of aluminum and composed by: base support; trolley (relative motion made through internal bearings); loading screw; KRATOS load cell SV50 model capacity 50 Kgf with signal indicator; support base of the tweezers (Figure 1).

The pressure applied on the edges of incision through of moviment of the tweezers and load screw to close the clamp base. In this case, the load is applied through a relationship of loading to the tip. This selection depends on the shape and size of the tweezers used.

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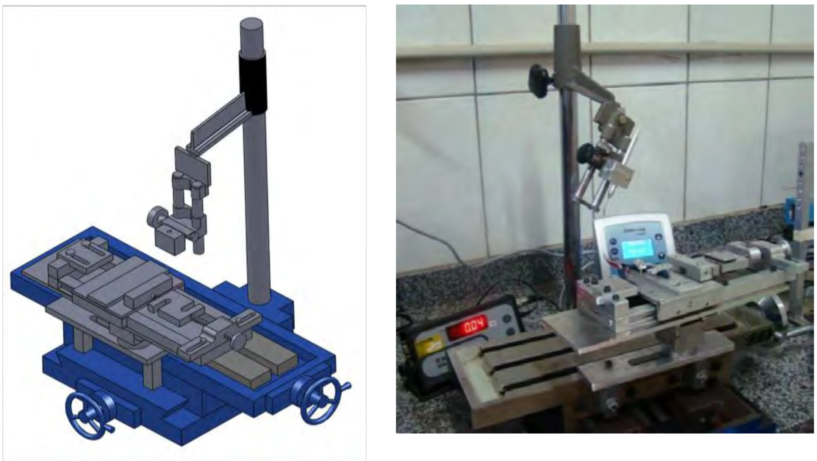

(a) (b)

Figure 1 – Draft of the experimental machine developed in environmental Solidworks®

During the welding process the pressure on the skin is applied by contact area in the region of the tip of the tweezers calculated from a sum of forces around the articulation of the tweezers given by:

$$P = F_1 (d_1 / d_2)(1/A) \qquad (1)$$

where (A) represents the area in contact with the tissue edges; (F_2) the force applied to the tip of the tweezers. The force (F_2), which is unknown, is determined by the force (F_1) controlled by the operator through the screw drive coupled to the load cell.

A diode laser system (λ = 808 nm) with a maximum output power of 4.5 W was used during the experiments. In order to evaluate the influence of laser power on union of tissues (skin), was used three levels of power: 0.5; 1; 1.5 Watts. In this work, was decided to evaluate the tissue welding only in continuous mode.

3.2 Sample Skin

In this study, an *in vitro* analysis using a laser source and pig skin was developed. In this case, the skins were obtained without the use of animals prepared specifically for this purpose. In this case, it is not necessary to conduct the experiement under a protocol approved by Care Ethics Committee due to simplification of the *in vitro* study.

Here the pig skin was used in order to simulate a human skin welding process, because according to Sullivan et al. (2001), anatomically and physiologically the pig skin is similar to human skin.

Figure 3 describes various steps from sample preparation skin to welding of skin samples.

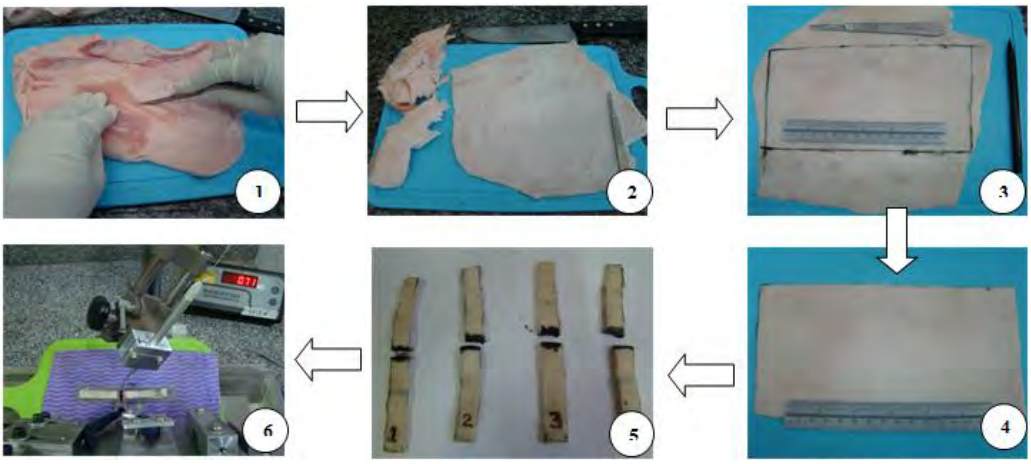

Figure 3 – Flowchart of the process preparation to laser tissue welding process.

According to Fig. 3, in step 01 is made a superficial cleaning of skin samples by removing excess fat; in step 02 with the scalpel the skin is left as uniform as possible, leaving only the epidermis and the dermis and a thin layer of fat; in step 03 is a markup for the sample cuts using a pen for drawing; in step 04, with a ruler, the samples is cut into strips of approx. 100 x 12 mm; in step 05 is made a full thickness incision at samples. At that point samples are prepared to

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undergo the welding process, except those which must be added the solders. In step 06 samples are placed in the experimental apparatus for the welding procedure. The entire process described was conducted at room temperature. Table 1 summarizes the parameters used for the laser tissue welding.

Experimental tests analyzed 12 different settings for welding, which is the combination of the parameters defined in Tab. 1. For each configuration were performed three tests replicates given a total of 36 different analysis. The nomenclature used in this work for the experimental planning as shown in Tab.1 is given by: power (W); pressure (P); no pressure (SP); solders (M); no solders (SM).

Table 1- Parameters used during the welding process of skin.

Power output [W]	Solders	Pressure [kPa]
$W_1 = 0,5$	M = albumin + “india ink”	P ≅ 693
$W_2 = 1,0$	SM = no solders	SP = no pressure
$W_3 = 1,5$	--------	---------

For this analysis, skin samples were obtained with conventional sutures. The incision was reduced with suture with simple point with nylon n° 5. The distance between needle entrances to tissue was approximately 6 mm.

3.3 Mechanical Tensile Tests

The influence of some parameters related to the skin and welding process was evaluated through the tensile strength and maximum strain for different welding conditions of tissue closure.

Tensile strenghts tests on pig skin samples were performed with a Filizola testing machine. The load cell capacity was 100 N and the welded and sutured samples was tasted at 2 mm/min and 10 mm/min crosshead velocity respectively. Force versus displacement curves were recorded and the data taken into Excel® to be processed and analyzed. The Figure 2 shows the machine used during the tensile tests.

Figure 2 – Machine used for tests highlighting the grips for holding specimen.

3.4 Skin Temperature Gradient

In order to take the skin temperature, is presented in this article, mathematical models to evaluate analytically the heating phenomenon by laser source was proposed.

For this an experimental apparatus to evaluate the temperature gradient *in vitro* was designed to measure the temperature at different distances from the surface irradiated by the laser, that is, different positions along the thickness of the skin. Figure 4 shows schematic drawing of the experimental apparatus used in this project.

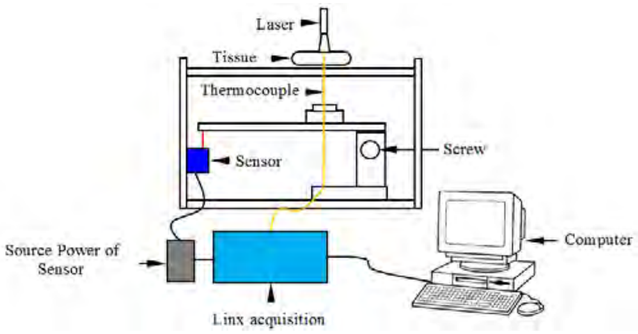

Figure 4- Schematic drawing of experimental apparatus used to measure the temperature along skin.

According to the Fig. 4, when the screw was rotate, thermocouple support structure moved vertically through the thickness of skin. To perform this procedure the skin samples in rectangular shape and thickness of approximately 10 mm receive holes spaced 10 mm to each other, as shown in Fig. 5. The thermocouple type K used had a relatively rigid tip of 2 mm diameter which does not allow any effect of buckling during the moviment into the holes. In addition, the holes had 1.5 mm diameter and was closed slightly due to fat layer. Although this procedure to be an approximation, since the laser was applied in the region close to the hole, several pre-test conducted showed good results when compared to the number of samples tested.

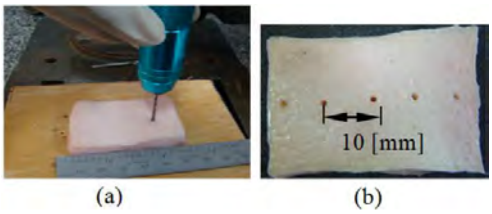

Figure 5- Sample preparation for evaluation of temperature (a) drilling of skin to pass the thermocouple (b) sample ready to be tested.

The thermocouple was moved inside the holes to mesure the temperature levels while skin was subject to laser radiation. The laser sensor was placed in association with thermocouple. The temperature signals and displacement were recorded synchronized.

The thermocouple was placed at the bottom of sample at the beginning of each acquisition and every 15 seconds the position of thermocouple varied in increments of approximately 1 mm within the skin toward the surface. This variation was made manually while skin was subject to laser radiation. This procedure was repeated for the remaining holes. Figure 6 shows the thermocouple during the acquisition of data while the laser radiation was applied to the top of hole.

To perform the experiment, each sample received six holes. It was used 03 sample for each level power output, i.e., 0.5, 1.0 and 1.5 Watts. The tests were conducted with the aid of the laser system used for welding incisions, a laser displacement sensor without contact (SICK OD30-04N152), a thermocouple (type K) and signal acquisition system of Lynx coupled to a microcomputer.

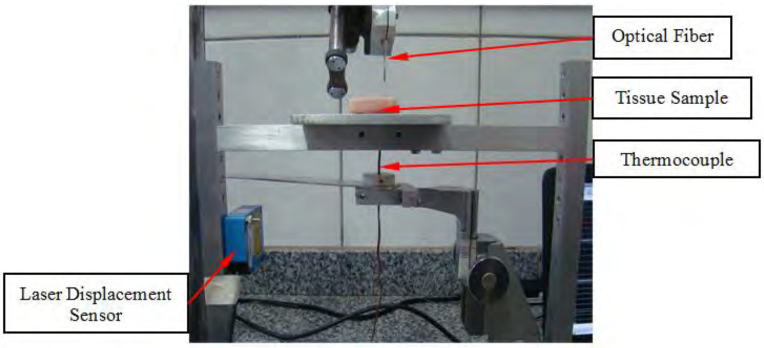

Figure 6 – Thermocouple used to measure temperature of sample skin subject a laser radiation.

4. MATHEMATICAL MODELING

Thermal behavior skin tissue is mainly a heat conduction process coupled to complicated physiological processes, including blood circulation, sweating, metabolic heat generation, and, sometimes, heat dissipation via hair or fur above the skin surface. The thermal properties of skin vary between different layers; even within the same layer, there exists large non-homogeneity and anisotropy due to the presence of blood vessels. Both the physiological processes and thermal properties of skin are influenced by a variety of factors such as temperature, damage, pressure, age, etc. To complicate matters, skin is an active, self-regulating system: heat transfer through the skin dramatically affects the state of skin, which can lead to the redistribution of skin blood flow over the cutaneous vascular network, whereby influencing the termal response of the skin tissue (XU et al., 2007).

4.1 Mathematical model adapted from models *in vivo*

Since the appearance of Pennes' bioheat equation, a variety of heat transfer models in different tissues of human body have been proposed, where the body tissue may be represented as a homogeneous continuum material with an embedded hierarchical vascular network (LUBASHEVSKY; GAFIYCHUK, 2004). The Pennes equation for modeling skin heat transfer is given by

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$$\rho c \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial z^2} + \varpi_s \rho_s c_s (T_s - T) + q_m + q_e \tag{2}$$

where ρ c and k are the density, specific heat and thermal conductivity of skin tissue, respectively; ρ_s and c_s are the density and specific heat of blood, ϖ_s is the blood perfusion rate; T_a and T are the temperatures of blood and skin tissue, respectively; q_m is the metabolic heat generation in the skin tissue and q_e is the heat generated by other heating methods such as laser.

In the present study, a one-layer model is proposed first for the theoretical analysis of heat transfer in skin, where the skin is treated as a homogenous medium with constant properties. One-dimensional (1-D) case is studied, as shown in Figure 7, which is a good approximation when heat mainly propagates in the direction normal to the skin surface (e.g. during laser heating) (XU et al., 2007).

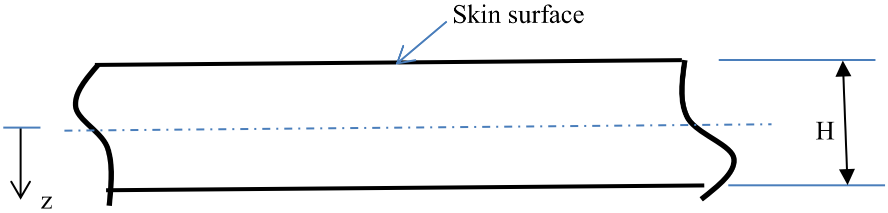

Figure 7 – Skin model used to evaluate the thermal gradiente. Similar model proposed by Xu et al., (2007).

According to Xu et al., (2007), the skin can be approximated by a one-dimensional flat plate of thickness (H) where the cartesian sistem are embedded at the center of the plate, as shown in Fig.7. If the flat plate is heated at a constant flux f_2 (t) while the bottom of the skin tissue is at body temperature, Tc, the boundary conditions can be written as,

$$-k \frac{\partial T}{\partial z}\bigg|_{z=H} = f_2(t) \tag{3}$$

$$T(z = -H/2) = T_c \tag{4}$$

Considers that initially, the skin has a temperature distribution $T_0(z)$ (before exposed to a heat flux) is

$$T(z,0) = T_0(x) \tag{5}$$

T_0 is the initial base temperature which in turn can be calculated by solving the problem in steady state given by:

$$k \frac{\partial^2 T}{\partial z^2} + \varpi_s \rho_s c_s (T_s - T) = 0 \qquad -\frac{H}{2} < z < \frac{H}{2} \qquad t > 0 \tag{6}$$

and subject to the boundary conditions

$$k \frac{\partial T_0}{\partial z} = h(T - T_\infty) \qquad z = H/2 \tag{7}$$

$$T_0(z) = T_c \qquad z = -H/2 \tag{8}$$

where h is the heat transfer coefficient between the middle and the skin. Xu et al., (2007) proposes a solution to the problem through a change of variable given by

$$w(z,t) = [T(z,t) - To(z)] e^{\left(-\frac{\overline{wb}\rho_b c_b}{\rho c}\right)t} \tag{9}$$

Replacing Eq. (5.8) in Eqs. (5.1-5.4), Eq.(5.1) can be change to,

$$\frac{\partial W}{\partial t} = \frac{1}{\alpha}\frac{\partial^2 W}{\partial z^2} + \frac{(q_{ext}(z,t) + q_{met}(z,t)) e^{\left(-\frac{\overline{wb}\rho_b c_b}{\rho c}\right)t}}{\rho\, c} \tag{10}$$

Using Green functions with boundary conditions (5.6 and 5.7) and processing (5.8) the corresponding solution of Green's function can be written as

$$T(z,t) = T_o(z) + \frac{2\alpha}{k\,H}\left[f_2 + k\left.\frac{dT_0}{dz}\right|_{z=0}\right] \times \sum_{m=1}^{\infty} \frac{\cos[\beta_m(z + H/2)]}{\alpha\,\beta_m^2 + \frac{\rho_b c_b \overline{w}_b}{\rho c}} \left(1 - e^{-\alpha\,\beta_m^2 t - (\overline{wb}\rho_b c_b/\rho c)t}\right) \tag{11}$$

where $\beta_m = (2m-1)\pi/2H, \quad m = 1,2,3, \ldots.$
and the initial temperature given by Xu et al., (2007) as being

$$T_o(z) = T_a + \frac{Q_m}{\rho_b c_b \overline{w}_b} + \frac{\left(T_c - T_a - \frac{Q_m}{\rho_b c_b \overline{w}_b}\right) \times \left[\sqrt{A}\cosh(\sqrt{A}x) + \frac{h_0}{k}\,\mathrm{senh}(\sqrt{A}x)\right]}{\sqrt{A}\cosh(\sqrt{A}\,L) + \frac{h_0}{k}\,\mathrm{senh}(\sqrt{A}\,L)} + \frac{\frac{h_0}{k}\left(T_\infty - T_a - \frac{Q_m}{\rho_b c_b \overline{w}_b}\right) \times\ \mathrm{senh}\left[\sqrt{A}\ (l - x)\right]}{\sqrt{A}\cosh(\sqrt{A}\,L) + \frac{h_0}{k}\,\mathrm{senh}(\sqrt{A}\,L)} \tag{12}$$

where $(A = \rho_b c_b \overline{w}_b / k)$

The mathematical model for the thermal gradient was adapted for *in vitro* studies using pig skin and specific experimental procedure to estimate the temperature along the thickness of the skin (To (z)). To evalute the model the following parameters were considered for the pig skins samples: H = 0.008 [m], ρc = 106 2.846 [J/K m^3], $\omega_b = 0$, K = 0.37 [J/mK] $\alpha = 1.3\ 10^{-7}$ [m^2/s] (XU et al., 2007).

4.2 Mathematical model proposed

This work proposed a mathematical model for evaluate the temperature gradient in pig skin using *in vitro* studies to validate and obtain the predictive equation through similitude techniques in engineering and data obtained via experimental analysis. The analysis is based on Buckingham's theorem (MURPHY, 1950) that can be used to develop prediction equations. The main advantage of dimensional analysis is reduce the number of variables which must be investigated. In this case π-terms or dimensionless parameters related to the phenomenon being studied is obtained through experiments. For *in vitro* study the goal was to estimate the temperature gradient in the skin, since the thermal gradient is the most important parameter in the laser tissue welding. Therefore, the following variables were found to be influence,

$$T = F\left[W,\, t,\, d,\, c,\, \rho,\, k,\, h\right] \tag{13}$$

The Eq. (6) indicates that temperature effect (T), proposed in this study, depends on the intensity of laser power (W); laser application time (t); temperature measurement distance into the skin (d); specific heat of skin (c); density of skin (ρ); thermal conductivity (k); thickness of skin (h). Equation (6) can be written considering a formulation of dimensional analysis, i.e.

$$T^{c_1}\, t^{c_2}\, \rho^{c_3}\ d^{c_4}\ W^{c_5}\ c^{c_6}\ k^{c_7}\, h^{c_8}\, C_\alpha = 1 \tag{14}$$

Developing the model π-terms obtained are:

$$\pi_1 = \frac{T\rho c^2 t}{k}; \quad \pi_2 = \frac{W t^3}{\rho h^5}; \quad \pi_3 = \frac{d}{h}; \quad \pi_4 = \frac{tk}{\rho c h^2} \tag{15}$$

Under certain conditions, it is possible to obtain predictive equation in terms of dimensionless parameters determined previously. In this case, these parameters were selected in order to obtain experimentally the temperature (T) by modifying 03 variables in the phenomenon, source power of laser (W), temperature measurement distance from the surface of the skin (d) and laser application time (t). The variables related to the characteristics and properties of skin were kept constant, since, *in vitro* tests were carried out on pig skin. The analysis carried out it was considered the environment temperature constant and, therefore, was not considered in the model. The goal was to reduce the parameters of equations and variables and simplify the amount of tests to be carried out. The component equations were considered as a product function π 04-terms, i.e.

$$\pi_1 = F(\pi_2,\, \pi_3, \pi_4) = \frac{F(\pi_2,\, \overline{\pi}_3,\, \overline{\pi}_4)\cdot F(\overline{\pi}_2,\, \pi_3,\, \overline{\pi}_4)\cdot F(\overline{\pi}_2,\, \overline{\pi}_3, \pi_4)}{F(\overline{\pi}_2,\, \overline{\pi}_3, \overline{\pi}_4)^2} \tag{16}$$

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The π-terms were obtained via experimental analysis and finally the predictive equation that describes the thermal gradient in the pig skin in vitro, can be written as,

$$T = 1,023 \times 10^{9} \times e^{1,116(d/h)} \times \frac{k}{\rho c^{2} t} \times \left(\frac{W t^{3}}{\rho h^{5}} \right)^{0,440} \times \left(\frac{t k}{\rho c h^{2}} \right)^{0,377} \tag{17}$$

To compute the component equations and their π-terms some variables were considered constants, the values of pig skin properties adopted are: ρ = 800 [kg/m3], k = 0.16 [kgm/° Cs ³], c = 3767 [m2/° Cs ²] (PEARCE; VALVANO, 2009).

5. RESULTS

The samples subjected to welding without solder material (SM) presented a darker in some points indicating a located dehydration. All samples welded without solders did not present an effective closure of edges of incision. On the other hand, samples subject a laser radiation with solder material presented an effective closure. With respect to the visual aspect in samples welded, it is difficult to characterize the degree of dehydration, because due to addition of dye all the incision was with a dark color. However, looking at the sample cross region, there was no significant difference regard to the dehydration degree and, in addition, the area of the incision of the samples was flexible as shown in Fig 8.

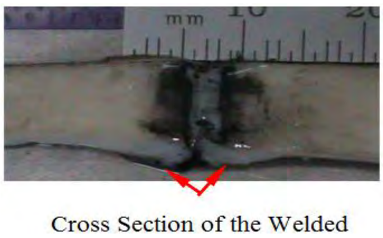

Figure 8 – Sample welded with solder material highlighting the cross section of sample.

With respect to samples welded, can be noted several factors that influence the process. Among these factors, the ability of the operator may be one of the most influential parameters, i.e., to achieve a homogenous weld with a clearly defined start and end point is a task that requires skill and experience. This process gets even more complicated considering others combinations of parameters, e.g., use or not solder materials, characteristics and properties of the skin and parameters of laser system. Figure 9 shows one of the samples analysed which homogeneous weld was reached.

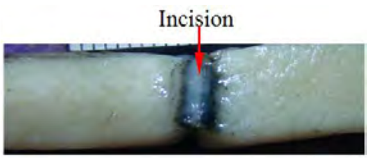

Figure 9-Sample welded with solder material, illustrating the homogeneity of weld.

5.1 Tensile Test

Only the welded samples with solder material had an effective closure. Therefore, only 19 mechanical tensile tests were carried out, this means 53% of total samples (36). Mechanical tensile tests were carried out on the samples submited to conventional suture. Table 2 shows data relating to breaking loads and displacement to the set according Tab.1.

Table 2 – Mean values for breaking load and displacement refers to the ultimate load.

Configuration	Max. Load [N]	Max.Displ. [mm]	Configuration	Máx. Load [N]	Máx.Displ. [mm]
W_1_P_M	0,5	3,27	W_2_SP_M	1,18	4,38
W_1_SP_M	0,4	2,54	W_3_P_M	0,19	1,88
W_2_P_M	0,35	4,76	W_3_SP_M	0,25	1,69

It is important to note at this point that the failure of union was considered at the beginning of the first decay of force versus displacement curve. This means that at this time the weld does not support the force applied. This "decay" represents a small opening along the welded incision.

The tensile tests was conducted until the rupture of the knots. However, in this work, the failure that indicated the maximum load was considered to be the tear of tissue by wires at holes as shown in Fig.10.

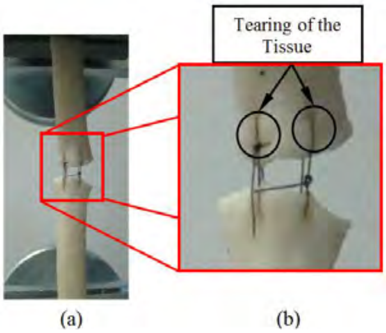

Figure 10- Tensile test on sutured sample. (a) sample placed between the grips (b) enlargement at region highlighting the tearing of the tissue.

The displacement and load of failure are 5,15 mm and 3,71 N respectively. In general terms, the meaning values of tensile strength of sutured samples are on the order of 3 to 10 times higher than welded samples. However, the incision remains open during the first postoperative days.

5.2 Mathematical modeling

Equations (5)-(12) require knowledge of initial function of temperature at a given position along the skin (To (z)). To estimate this function an experimental apparatus was designed. It should be emphasized that for these tests the initial reference point (z = 0) indicates the bottom of skin. Table 3 shows the resulting equations and their derived for each power source.

Table 3 – Equations of the distribution of temperature (To (z)) and their respective derivatives.

$f_2(W/cm^2)$	To (z)	dTo(z)/dz
50	$0,1108z^2 – 0,119z + 25,272$	0,2216z - 0,119
100	$0,4803z^2 – 0,2067z + 28,229$	0,9607z – 0,2067
150	$0,3744z^2 + 0,2228z + 30,085$	0,7488z - 0,2228

Figure 11 shows the temperature curve as a function of time for mathematical models adapted. It turns out, by the behaviour of the curve relative to the surface of the skin (z_1 = -H/2), the level of temperature increases over time while the heat source acts on the surface and this is because there is no effect of blood perfusion. The plots for the 1 and 1.5 Watts are similar.

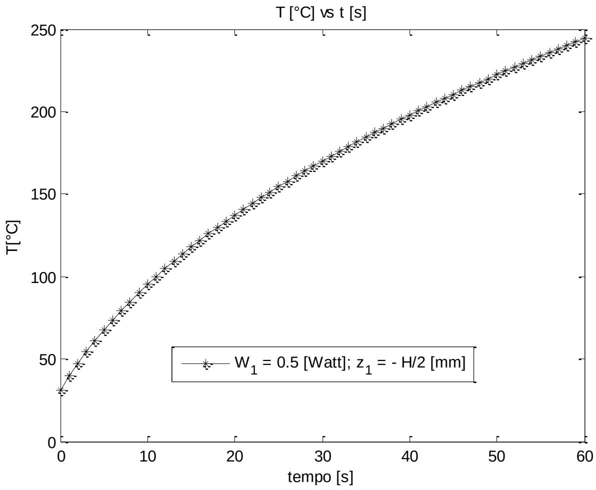

Figure 11-Temperature versus time adapted from the mathematical model (W_1=0.5 [W]; z_1=-H/2)

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Temperature measured experimentally with predictive equation showed a good correlation between values. Table 5 shows values of distance measured from the base of skin and its corresponding temperature and the temperature calculated by predictive equation and the error.

Table 5 – Temperature values measured experimentally and calculated by the predictive equation as a function of distance.

d [m]	Experimental Temperature [°C]	Similitude Temperature [°C]	Error [%]
0,001	27,7	26,6	4,27
0,002	29,3	29,7	1,33
0,003	29,4	33,2	12,94
0,004	31,8	37,1	16,9
0,005	42,9	41,5	3,33
0,006	47,5	46,4	2,23

6. CONCLUSION

The healing process is a biological phenomenon that starts at the time of damage of living tissue. Over time, through the healing process the incision acquires higher strenght. As the study has been developed in this work *in vitro*, the only force on the repair is due to protein denaturation of solder material.

There is a high variation in values obtained for tensile test demonstrating a great nonlinearity of welded closure. Several factors can influence this process connected with adherence of tissue under the conditions evaluated and mainly due to difficulties in realization experiments. Among these difficulties can be highlighted: sample preparation; application of pressure on the edges of the incision; amount of solder material; skill of the operator; proper handling of welded samples; proper positioning of the samples on the test machine.

It is possible to obtain an immediate closure of the incision through the process of laser welding, even in vitro. In the point of view in vivo, this could represent an advantage, since the biological healing phenomena are acting to restore the continuity of the tissue and its strength.

7. ACKNOWLEDGEMENTS

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