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EXPERIMENTAL STUDY OF HEAT TRANSFER IN ENDOVENOUS LASER TREATMENT

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Abstract. *The endovenous laser treatment (EVLA or EVLT) is a minimally invasive surgical technique for vein cauterization, which aims to interrupt the blood flow and eliminate varicose veins. This study presents an experimental investigation of the heat transfer mechanisms in this procedure, employing an artificial vein model. This model was manufactured with a polymer, moulded in a cylindrical shape with a central orifice in the axial direction, which was filled with human blood during the experiments. To mimic the laser treatment in vivo, a laser fiber was driven through the interior of the vein model at a constant speed and temperature measurements were obtained with a series of thermocouples installed in the axial and radial direction. The data obtained showed an asymmetry in the temperature field and its magnitude was related to the following effects: (1) displacement of the fiber tip out of the vein's centerline during the test; (2) direct contact of the fiber tip with the vein wall, and (3) steam bubbles formed at the fiber tip moving upwards due to buoyancy.*

Keywords: *Endovenous laser treatment (EVLT), Heat transfer in biological systems, Bioengineering.*

1. INTRODUCTION

Chronic venous insufficiency (CVI) is a common disease with the worldwide prevalence. People affected are more predisposed to develop specific conditions like CVI of lower limbs, commonly known as varicose veins of lower extremities. Varicose veins are a degenerative disease of the venous system, which changes the vein anatomy associated with valvular dysfunction, resulting in reflux (reverse or retrograde flow) in affected areas of the superficial venous system of the legs, "(Bergan, 2007; Heger *et al.*, 2014)".

According to "Golledge and Quigley (2003)", varicose veins affect 10 to 40 % of the world population aged 30 to 70 years old. The early symptoms reported include pain and fatigue, followed by twisted and bulging veins. More severe cases are followed by venous ulcers, which are superficial injuries arising from local trauma, affecting the people quality of life directly, "Heger *et al.* (2014); Rasmussen *et al.* (2007)".

The direct treatment for this condition is the elimination of the blood reflux at the vein. Historically, the usual treatment for this illness has been an open surgery with complete extraction (stripping) and ligation of the defective vein. Nowadays, besides the stripping procedure, other treatments are available, divided into thermal and non-thermal. Foam sclerotherapy is the main non-thermal treatment used, while radiofrequency (RFA) and laser ablation are the thermal alternatives.

Since the introduction of the endovenous laser ablation or treatment (EVLA or EVLT) procedure, several studies regarding to the physical mechanisms elucidation of this technique were developed. Regarding to EVLT, it presents a good acceptance by doctors due to the good results obtained in respect to vein occlusion and at the postoperative, "(Bootun *et al.*, 2016; Heger *et al.*, 2014; de Medeiros, 2006)".

The EVLT procedure consists of using laser energy to cause injury at the vein wall, also develop local thrombosis due to the blood reaction with temperature. After the procedure, blood vessels become thrombotically occluded which trigger a chronic type inflammatory response that mediates tissue remodeling (cicatrization) and ultimately permanent closure, "(Heger *et al.*, 2014)". The laser is conducted through an optical fiber, which can be bare or radial tip.

Light and other electromagnetic energy sources are composed of elementary particles known as photons, and its propagation described as an electromagnetic wave with specific lengths, varying from gamma rays, for small wavelengths, to radio waves, for large wave lengths. All lasers devices are monochromatic, i.e., they emit light in just one specific wavelength. Basically, the laser systems have four parts: a system of energy source, an optical resonant cavity, the active medium and the delivery system involving optic fiber or mirrors. Inside of the laser system, after the active medium be excited and due to the propagation and the increase of photons volumetric density, when these move in a parallel direction,

leave the cavity in a pattern of laser beam, the beam can be conducted through mirrors or optical fibers up to the local of laser application, “(Franck *et al.*, 2016)”.

Blood and the tissue that composes the vein contain light absorption elements known as chromophores, which presents strong light absorption at specific wavelengths of the electromagnetic spectrum, “(Vuylsteke and Mordon, 2012)”. The interactions between the laser beam and biological materials occur via absorption and scattering of photons at the medium. The photons that contains high energy when absorbed, cause an photothermal effect, which increase the temperature due to the energy absorption. The photons that are not absorbed at the proximity of the laser beam is delivered, scatters to the material and are absorbed by chromophores far from that area. At the EVLT procedure, these photons when are not absorbed directly by the blood, can be absorbed by the vein wall, which also cause the photothermal effect to the tissue, “(Franck *et al.*, 2016)”.

The procedure application its being performed by doctors for a considerable period of time, the mechanisms of action are still under debate and being reported in developed studies in surgery and other research areas, as in laser science field. The knowledge about the mechanisms of action of the EVLT is it utmost importance not just to improve the efficiency of the technique but also to avoid postoperative complications. “Bergan (2007)” highlight that the laser uses is recent to the varicose veins treatment, and the mechanisms of action are still in discussion.

The studies of “Srinivasa *et al.* (2018), van der Geld *et al.* (2010), van den Bos *et al.* (2009), and Disselhoff *et al.* (2008)” present descriptions about the EVLT’s mechanism of action, which, as of yet, is not totally elucidated. They discuss several phenomena like the direct absorption of light by the fluid and solid phases, the contact of the fiber tip with the vein wall, the steam bubble formation, and the heat pipe effect that involves the classic mechanisms of heat transfer i.e. boiling and condensation, convection and conduction. The main interest is to comprehend the phenomena that rule the heat transfer in the procedure, of course, the non-uniformity of the vein’s diameter imposes an additional difficulty in developing the analysis of the problem. For this reason, some experimental studies were proposed, in especial, with interest to support some hypothesis and analysis that have been developed. Examples of these are the “Fan and Rox-Anderson (2008); Disselhoff *et al.* (2008); Proebstle *et al.* (2002)” studies.

Aiming to add knowledge, to better understand its mechanism of action and to provide insights for enhancements, this work presents the development of an experimental workbench to reproduce *in-vitro* the EVLT procedure. The model has significant simplifications but, even so, is capable to emulate the phenomena involved at the surgical procedure, thus allowing the study of temperature field and the effects of some physical and mechanical parameters.

2. MATERIALS AND METHODS

The experimental apparatus consists a system with the capability to simulate a human body condition (body temperature or another of interest), including a vein prototype, allowing the endovenous laser treatment reproduction *in-vitro* at an artificial blood vessel. The idea is to obtain the temperatures at the inner vein wall. These temperatures were obtained using a DAq system coupled to the model. Figure 1 exemplify the experimental workbench.

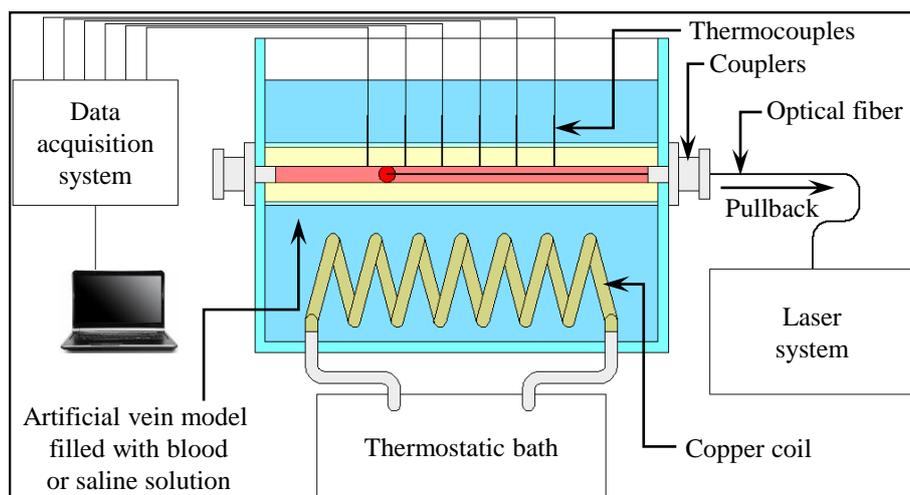


Figure 1. Experimental workbench setup representation

The vein prototype consists in a cylinder of a polyvinyl chloride with plasticizer (PVC-P) molded inside a transparent cylindrical tube of acrylic. The vein model had an external diameter of 34 mm, a length of 250 mm and a central orifice along its length with a diameter of 8 mm. The vein prototype was immersed and attached to an acrylic reservoir filled with water 4 cm up to the model. The reservoir also had a copper serpentine which is connected to a thermal bath thus allows the control of the reservoir temperature.

To obtain the temperatures, the artificial vein was instrumented with thermocouples E type manufactured by OMEGA. A set of 48 thermocouples were used distributed in the radial direction spaced 45° between each (a total of 8 at the section), and at the axial direction the section was replicated 6 times, with a distance between each of 10 mm, positioned at the internal radius of the model to measure the temperature at the internal wall. To measure the temperatures were employed two data acquisition units Agilent model 34972A, with two modules 34901A manufactured by Keysight. The modules had twenty channels of reading each, but just 12 channels were used by thermocouples. These two equipments composes the data acquisition system (DAQ) that was connected to a laptop and controlled the software Agilent BenchLink - Data Logger 3.

The entire temperature measurement system, including thermocouples, connectors, extension wires and data acquisition system, was calibrated. The calibration was performed using the Testo 735 equipment with a temperature sensor PT100 to measure the reference temperature. The measurement uncertainty of the experiment was estimated as $\pm 0.76^\circ\text{C}$.

To attach the vein to the reservoir a pair of couplers were used, in which a central venous catheter was connected, thus allowing the filling of the model with human blood or saline solution and the introduction of the optical fiber. Blood was obtained at the Blood Bank from University Hospital of the Federal University of Santa Catarina.

Two laser system were used to performed the experimental tests with a wavelength of $\lambda = 810\text{ nm}$ manufactured by Synus Laser Technologies model Novadiode 30, operated at a continuous mode, the system had adjustable power varying from 1 to 30 W and with a diode active medium of neodymium-doped yttrium aluminum garnet (Nd:YAG). The second equipment used was with a wavelength of $\lambda = 1470\text{ nm}$ manufactured by ORlight Laser model Innova touch DUO also operated in a continuous mode, the system had adjustable power varying from 1 to 15 W, and the inert medium of the system is a diode of indium gallium arsenide phosphide (GaInAsP). The laser system with $\lambda = 810\text{ nm}$ interacts preferentially with the hemoglobin chromophore, and the other with $\lambda = 1470\text{ nm}$ interacts with the water chromophore.

Two types of fibers were used, a bare and a radial fiber, both with a core diameter of $600\ \mu\text{m}$. The radial fiber has a tip with a diameter of 2 mm. The bare fiber delivers the energy to the front direction in a conic shape. The radial fiber delivers the energy in the radial direction in a ring shape. Figure 2 presents the fibers, geometries and laser beam profile.

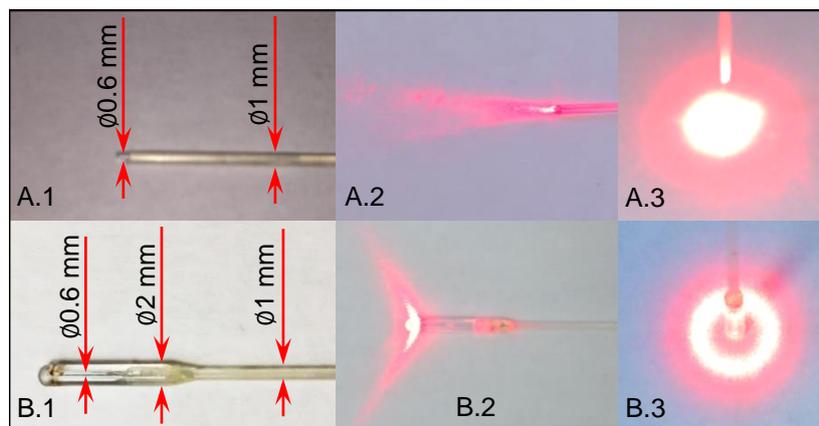


Figure 2. Bare fiber: (A.1) dimensions; (A.2) Light emission pattern at the side; (A.3) Light emission frontal pattern. Radial fiber: (B.1) dimensions; (B.2) light emission pattern at the side; (B.3) light emission frontal pattern.

The base parameters were chosen to reproduce clinical treatments. The power used was 12 W with the fiber stationary or a standard pullback velocity of 2 mm/s being the moving performed by hand. The fiber moving was performed with assistance of a metronome, a graduated scale at the side of the box and a delimited reference at the fiber. The initial temperature of the set was 30°C . At the surgical procedure a saline solution with lidocaine is injected at the periphery of the vein, this solution is usually at a room temperature (25°C) or below, being the external temperature of the vein lower than the human body temperature.

The experimental tests consist of the following steps. With the vein model attached to the reservoir and filled with blood or saline solution, the optical fiber is introduced into the catheter and positioned 50 mm forward of the first line of thermocouples. The temperature acquisition is triggered and after 10 seconds the optic fiber is pulled with a constant velocity (pullback), moving through all the instrumented sections. When the tip of the fiber reaches a position 50 mm from the last thermocouple section (about 160 mm from its starting point), the laser and the temperature acquisition are turned off.

3. RESULTS AND DISCUSSION

The tests were developed with different conditions, varying the laser system wavelength, the fiber type, fluid that fill the vein and fiber moving.

The first experimental tests were performed at the stationary condition, positioning the fiber tip at the center of the instrumented region without moving. The interest of this experiment was to observe the heat propagation from the fiber tip to the sections located in front and behind of the tip. The test was developed with the following conditions: $Q = 12 \text{ W}$, $\lambda_w = 1470 \text{ nm}$, and saline solution filling the vein. The system was activated maintaining the laser for approximately 90 s and turned then off. Figure 3 presents the maximum temperatures obtained at all the instrumented sections (in front and behind of the tip, respectively), using the radial fiber.

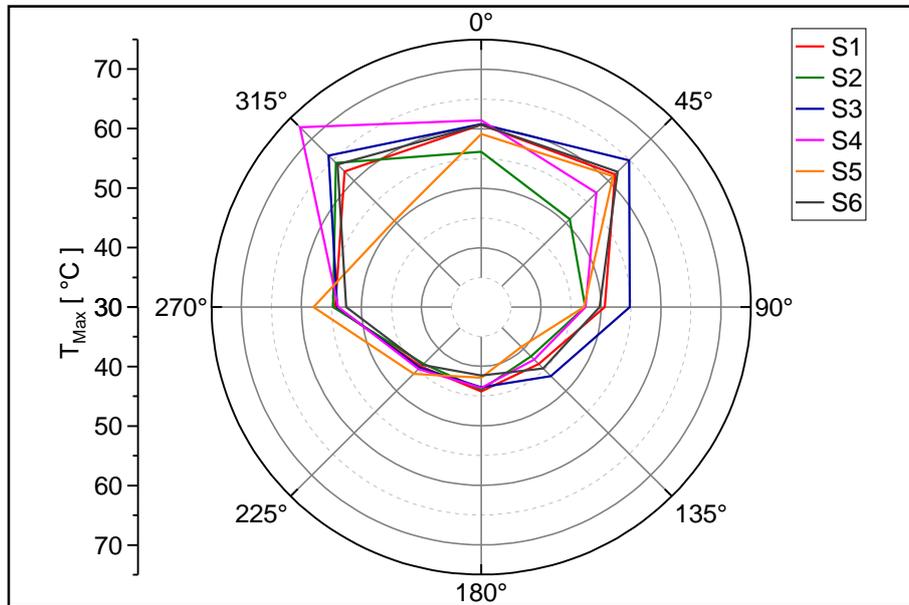


Figure 3. Maximum temperatures disposed at the angles in each section in a static test with the radial fiber positioned at the center of the instrumented region, with $Q = 12 \text{ W}$, $\lambda_s = 1470 \text{ nm}$, radial fiber, saline solution filling the vein, and laser activated for 90 s.

One can observe that the sections far away of the fiber tip, in front and behind, the thermocouples registered an increasing of the temperatures, being the maximum temperatures measured at the upper region of the vein model, with a higher and a lowest temperature approximately of $75 \text{ }^\circ\text{C}$ and $40 \text{ }^\circ\text{C}$, respectively. However, in respect of the initial temperature, the difference of the upper region (315, 0, and 45, as example) presented an average increase of $\Delta T = 30$ and the lower region (135, 180, 225) an average increase of $\Delta T = 15$. The results obtained with the bare fiber presented a similar behaviour as the radial fiber.

In respect of the experimental tests with the fiber moving, simulating the surgical procedure application at the artificial vein prototype, the following results were obtained. The following results present the temperature profiles of the thermocouples at the angle position 0° and 180° the upper and lower region, respectively, and for the all sections, 1 up to 6.

Figure 4 and Figure 5 presents the results for an experimental test using the following set-up: laser power 12 W; wavelength 1470 nm; pullback velocity 2 mm/s, bare fiber, and blood filling the vein model.

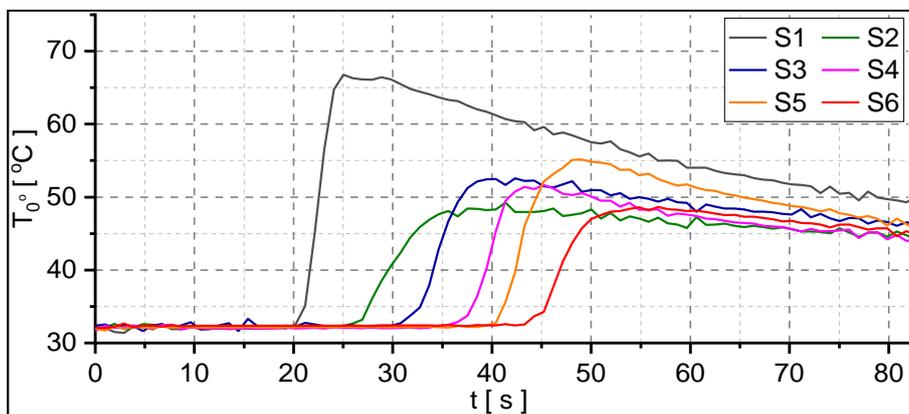


Figure 4. Temperature profiles of thermocouples for all sections positioned at the angle 0° , with $Q = 12 \text{ W}$, $S_q = 2 \text{ mm/s}$, $\lambda_s = 1470 \text{ nm}$, bare fiber, and blood filling the vein model.

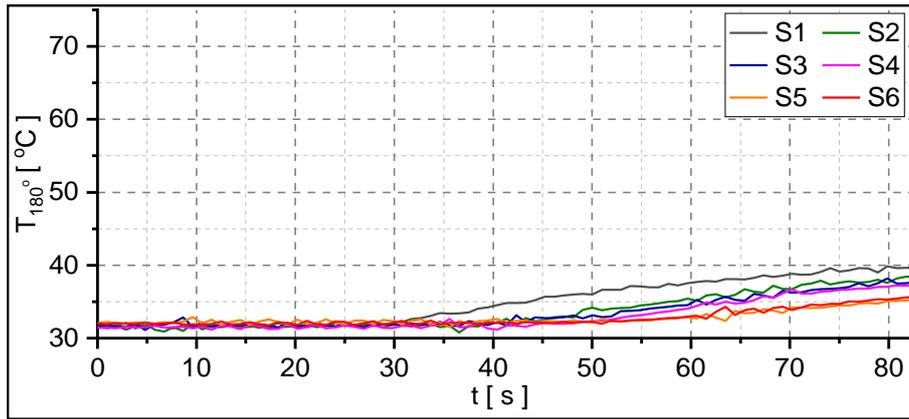


Figure 5. Temperature profiles of thermocouples for all sections positioned at the angle 180° , with $Q = 12$ W, $S_q = 2$ mm/s, $\lambda_s = 1470$ nm, bare fiber, and blood filling the vein model.

It is possible to observe that the asymmetry of the profiles temperatures is observed comparing these two angles positions. One can observe that practically all the sections at the upper region, presents a slight increase of the temperature followed by a suddenly peaks and subsequently the temperature decreasing. These profiles represent the fiber tip draw near and moving through the section and after moving away, leaving the local blood volume heated. The these results also lead to a deduction that the tip of the fiber is moving displaced of the centerline, and the higher temperatures at the superior part can be originated from the bubbles formation and its displacement.

Figure 6 and Figure 7 presents the temperature profiles the thermocouples following the. The following set-up was used: laser power 12 W; wavelength 1470 nm; pullback velocity 2 mm/s, radial fiber, and blood filling the vein model.

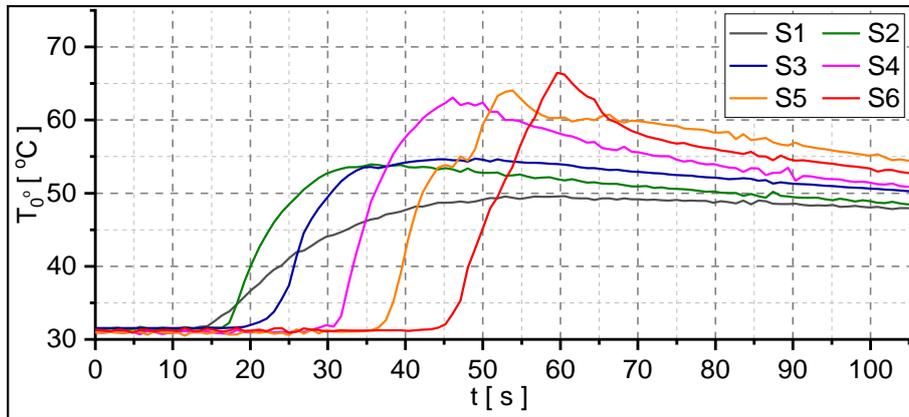


Figure 6. Temperature profiles of thermocouples for all sections positioned at the angle 0° , with $Q = 12$ W, $S_q = 2$ mm/s, $\lambda_s = 1470$ nm, radial fiber, and blood filling the vein model.

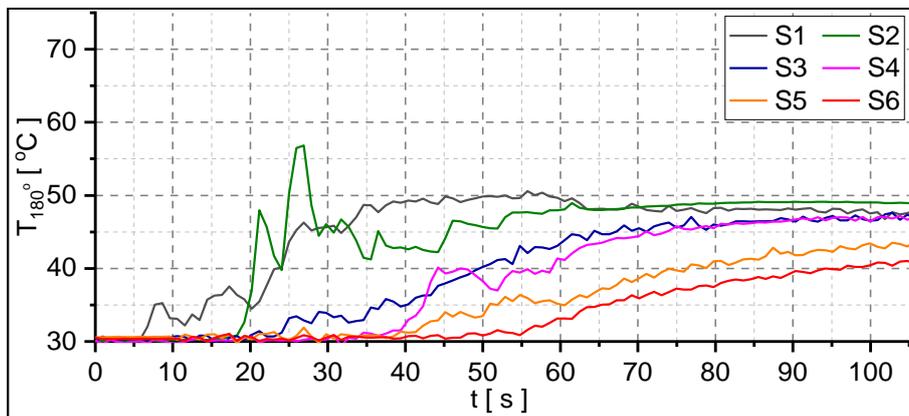


Figure 7. Temperature profiles of thermocouples for all sections positioned at the angle 180° , with $Q = 12$ W, $S_q = 2$ mm/s, $\lambda_s = 1470$ nm, radial fiber, and blood filling the vein model.

One can observe that the results between the bare and radial fiber presents some similarities at the temperature profiles when compared with the asymmetry and behaviour. The radial fiber presents more disorder in the temperature profiles, however, the thermocouples registered more temperature variation at the angles positions.

Figure 8 and Figure 9 presents the temperature profiles the thermocouples at the angle position 0° and 180° the upper and lower region, respectively, and for the all sections, 1 up to 6. The following set-up was used: laser power 12 W; wavelength 810 nm; pullback velocity 2 mm/s, bare fiber, and blood filling the vein model.

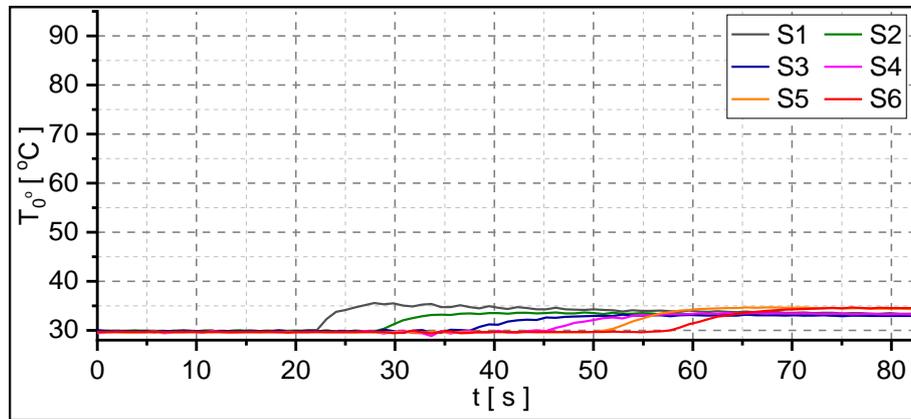


Figure 8. Temperature profiles of thermocouples for all sections positioned at the angle 0° , with $Q = 12$ W, $S_q = 2$ mm/s, $\lambda_s = 810$ nm, bare fiber, and blood filling the vein model.

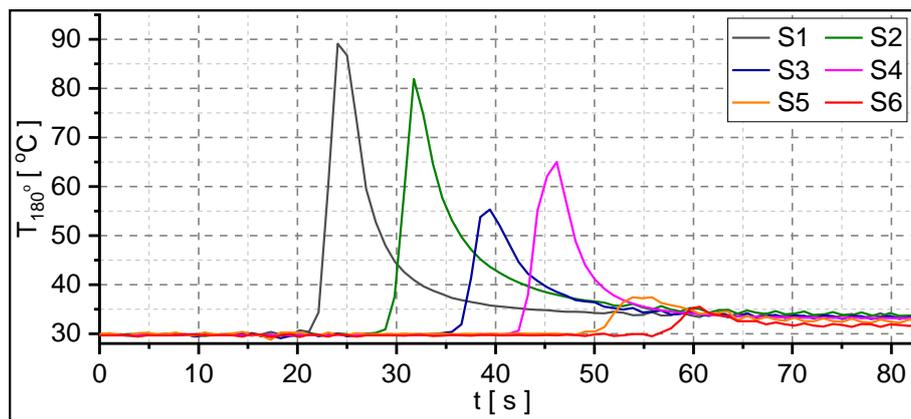


Figure 9. Temperature profiles of thermocouples for all sections positioned at the angle 180° , with $Q = 12$ W, $S_q = 2$ mm/s, $\lambda_s = 1470$ nm, bare fiber, and blood filling the vein model.

It is possible to observe that at this experiment the asymmetry was different than the others experiments, being the higher temperatures at the lower region and at the top the temperature did not presented an significant increase of the temperatures. These profiles at the lower region represent the fiber moving through the section and heating the area.

The these results lead to a deduction that the tip of the fiber is moving near to the wall of the vein model, beins possible the tip touching the surface and heating directly the region where the thermocouple tip was positioned.

Figure 10 and Figure 11 presents the temperature profiles the thermocouples at the angle position 0° and 180° the upper and lower region, respectively, and for the all sections, 1 up to 6. The following set-up was used: laser power 12 W; wavelength 810 nm; pullback velocity 2 mm/s, radial fiber, and blood filling the vein model.

One can observe also at this experiment followed a similar behaviour as the results presented at the Fig. 8 and Fig. 9, the upper region did not presented an increase of the temperature and the lower region presented the temperature variation. Being at this, the temperatures at the superior region was the same as the initial temperature.

Performing the experiment it was possible to observe the agglomeration of bubbles at the top of the vein model. “Fan and Rox-Anderson (2008)” had been observed this effect and reported in his study, this, how addressed at the previous studies cited already, is one of the mechanisms of heat transfer on the procedure, and the volume of it depends on the intensity of the laser energy and the pullback applied to the fiber, this leads to the quantity of energy delivered to the vein, also mentioned in medical field as LEED (Linear Endovenous Energy Delivered), “(Proebstle *et al.*, 2002)”. The steam with high energy travels from the fiber tip to the top of the vein by buoyancy, and through this movement also heating the volume of blood surrounding it.

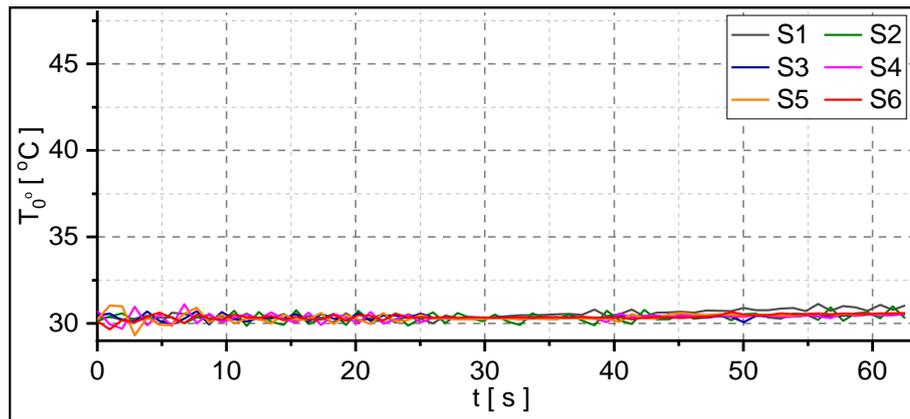


Figure 10. Temperature profiles of thermocouples for all sections positioned at the angle 0° , with $Q = 12$ W, $S_q = 2$ mm/s, $\lambda_s = 810$ nm, radial fiber, and blood filling the vein model.

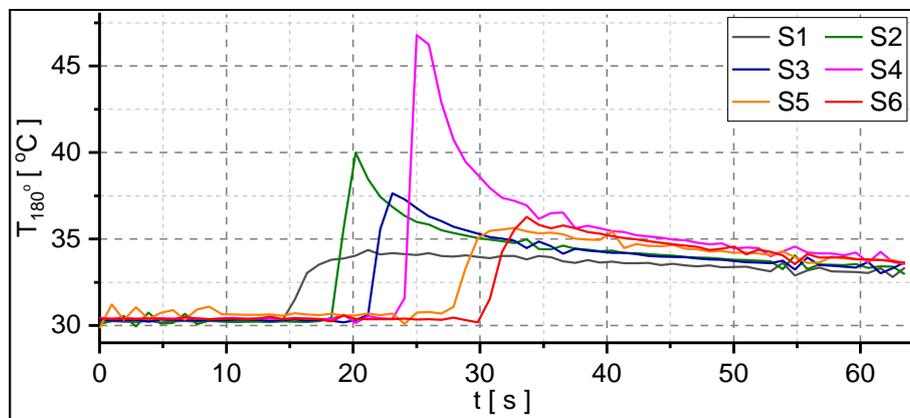


Figure 11. Temperature profiles of thermocouples for all sections positioned at the angle 180° , with $Q = 12$ W, $S_q = 2$ mm/s, $\lambda_s = 810$ nm, radial fiber, and blood filling the vein model.

When the bubbles were observed at the experiment and the temperatures at the upper region did not present difference compared with the initial temperature, the steam bubbles with high energy can condensate near of the fiber tip, increasing the blood temperature, and the visible bubbles at the superior part of the vein model can be non-condensable gases.

Other phenomena evolved that can justify the peaks of temperatures can be derived of the direct contact of the fiber tip with the vein wall, which is another described by some authors already mentioned.

4. CONCLUSIONS

The experimental apparatus developed for the *in-vitro* procedure showed good results in respect to the thermal control, temperature measurement and easy of assembling. The vein prototype shows good reproducibility and quality to be used in *in-vitro* tests. It presents sufficient resilience to allow for precision positioning of the thermocouples.

The results obtained through the measurement identify asymmetry in the temperature field of each vein section. This asymmetry was associated with some effects observed and including the measurements.

Throughout the experiment development, was possible to observe that the fiber tip moves out of the centerline, it can support the temperature differences observed between different angles of each section. This move implies significantly at the peaks of temperature at the inner wall, it can be provided by the direct contact of the fiber tip with it, this last was another effect related and observed in the results.

Due to the transparency of the model, was observed the steam bubble formation and that they move and concentrated at the top of the vein. These bubbles are generated at the fiber tip and had a large amount of energy, and because of the gravity effect, it moves to the top end up heating the blood volume at the superior part and, can be a different reason of the blood volume at the bottom do not have a significant increase of the temperature.

Finally, was observed that the experimental research development on this field can increase the knowledge about phenomena evolved in the procedure, and, also provide information and analysis that help doctors to improve the technique and in the obtention of better results.

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