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Wireless Vein and Artery Identifier for Laparoscopic Instruments

Identificador Inalámbrico de Venas y Arterias para Instrumentos Laparoscópicos

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ABSTRACT

This article presents an innovation on a conventional laparoscopic instrument, to which was added the automatic function to identify veins and arteries. It is proposed the use of a reflective-optical sensor with a specific work wavelength acting on blood vessels. The discrimination success between veins and arteries is achieved based on the range of difference between the light emitted and the light reflected. At the tip of a laparoscopic instrument was fitted a reflective-optical sensor composed of a LED and a light dependent resistor. In the upper part of the instrument an electronic control, processing and radio frequency transmitter module was fitted, which warns the surgeon and his assistants if the detected blood vessel is a vein or artery. The instrument was tested *in vitro* using whole human blood samples and *in vivo* on canine model blood vessels. With the innovation a low-cost support tool is achieved that could aid the surgeon when working on minimally invasive environments.

KEYWORDS: Laparoscopy; spectrometry; reflective-optical; wireless; absorption

RESUMEN

En este artículo se presenta una innovación realizada a un instrumento laparoscópico convencional, en la que se agrega la funcionalidad de identificación automática de venas y arterias. Se propone la utilización de un sensor óptico-reflexivo con longitud de onda específica, que actúa sobre los vasos sanguíneos. El éxito de discriminación entre venas y arterias se logra en función del rango de la diferencia entre la luz emitida versus la reflejada. A la punta de una pinza laparoscópica le fue adaptado un sensor óptico-reflexivo compuesto por un LED y una foto-resistencia. En la parte superior de la pinza, sobre el manipulador se adaptó un módulo electrónico de control, procesamiento y transmisión por radio frecuencia, el cual da aviso al cirujano y a sus asistentes si el vaso sanguíneo detectado es vena o arteria. El dispositivo fue probado *in vitro* utilizando muestras de sangre entera humana e *in vivo* sobre vasos sanguíneos de modelo canino. Con la innovación se logra una herramienta económica de apoyo para el cirujano que se desempeña en ambientes mínimamente invasivos.

PALABRAS CLAVE: Laparoscopia; espectrometría; óptico-reflectivo; inalámbrico; absorción.

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INTRODUCTION

In traditional surgery, skin layers are literally cut to access the abdominal cavity of the patient, thus leading to postoperative discomfort, large scars and extended recovery times. In response to these disadvantages, minimally invasive surgery appeared [1], which is oriented to developing techniques allowing minimal intervention in the physiological structure of the subject [2]. This is achieved by accessing the interior of the human body by making small incisions between 5-15 *mm* in diameter through which laparoscopic instruments (i.e. forceps, graspers, cauterizers, extractors, cameras, etc.) are introduced. One of the problems in laparoscopic surgery occurs when surgeons mistakenly cut arteries [3-6]. The National Practitioner Data Bank (NPDB) mentions that during the 1990-2004 period, there were 191,804 medical errors that took place just in the United States of America, of which 67% were attributed to qualified surgeons [7]. The deaths or consequences caused by these errors give as a result very high compensation fees [8]. In Mexico, traditional (i.e. non-laparoscopic) surgeons must observe the NOM-026-SSA3-2012 regulation [9], which stipulates all procedures for the practice of major outpatient surgery [10]. However, the real scenario is not very encouraging since overpopulation of pending surgeries, poor quality of equipment in the facilities, stress of the activity itself, and communication errors among the participants, involves developing alternative methods in the field to avoid accidentally cutting any artery. One of these processes is the thorough search of the physiological connection of the artery in question, which increases the time, costs and stress, and the challenge is even greater in a laparoscopic environment. Nevertheless, in the scientific literature, some proposals of devices designed to detect anatomical structures before performing some dissection in laparoscopic environments can be found. Most of these proposals usually implement somewhat complex devices and/or algorithms such as: standard and infrared cameras (i.e. infrared charge-coupled detectors), standard and infrared light sources, light filters, software and hardware for image processing, standard and infrared monitors etc., which could make these systems more expensive to bring to the market, not to mention that many do not have the capacity to differentiate between veins and arteries [11-13]. This article presents the innovation made to a conventional laparoscopic instrument (termed identifier), in which an automatic function of veins and arteries identification is adapted, using the light reflection technique [14, 15]. The identifier was tested *in vitro* with whole human blood samples and *in vivo* directly on canine model blood vessels.

METHODOLOGY

Hardware

As shown in Figure 1, a 5 *mm* WISAP laparoscopic forceps model MAI905330 was fitted with a reflective-optical sensor (ROS) composed of a LED and a light dependent resistor (LDR) VT43N2. On the upper part of the forceps, an electronic module composed of: an Arduino micro ATmega328 (μC) card, a radio frequency transceiver NRF24L01 (RFT), and a force sensitive resistor FSR-0.6 (FSR) were adapted to the manipulator.

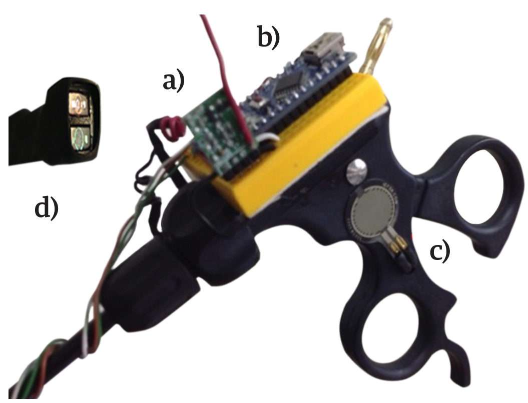

FIGURE 1. **A laparoscopic forceps showing the adaptation of the electronic components. (A) RF Transceiver, (B) Microcontroller, (C) Force Sensor Resistor and (D) Reflective-Optical Sensor**

When the surgeon presses the FSR with his thumb from the forceps manipulator, the LED of the ROS emits a light with a certain wavelength that impinges on the blood vessel to be identified either as an artery or as a vein. The LDR registers the light reflected from the blood vessel, converting it into voltage, which is collected by one of the analog inputs. The μC processes the data using a decision algorithm programmed in C++, which is explained in section "Automatic Detection". The decision made, whether it is a vein or an artery, is transmitted wirelessly to a receiver module via the RFT using a carrier frequency of 2.4 *GHz* with the intention that all the team involved in the surgery to be aware of the identification of the blood vessel. The receiver module also contains an RFT connected to a μC, which receives the decision and communicates it to the surgical team in an audible and visual manner. The receiver module activates a buzzer with an audible frequency of 250 *Hz* for veins and 1600 *Hz* for arteries, both with a duration of 250 *ms*. In addition to this, an RGB LED is issued by emitting a red or blue color if the blood vessel is identified as a vein or an artery, respectively. If the identifier is inactive or is in an indeterminate situation, the RGB LED emits a green light. Figure 2 schematically shows the transmitter and receiver modules.

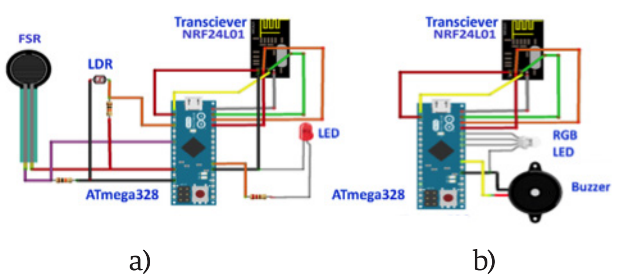

FIGURE 2. The components of (A) transmitter module that was mounted on the conventional laparoscopic instrument and (B) receiver module which can be remotely placed so that all the surgical team can see or hear the decision made on the blood vessel.

RESULTS AND DISCUSSION

In Vitro Tests

The identifier was tested with 5 venous blood samples and 5 arterial blood samples, which were taken from 10 different adults who went to a general hospital in northwest Mexico for different clinical reasons. Blood samples were placed in 3 *ml* vials and placed inside a dark chamber to test the identifier, and to avoid that the light emitted or read by the ROS was contaminated by other surrounding light sources (i.e. noise). The time, from the taking of the blood sample, its placement in the dark chamber, and the test with the optical-reflective device, was not more than 20 *minutes* to avoid the degradation of the sample.

Previous studies have shown that hemoglobin (Hb) and oxyhemoglobin (HbO_2) exhibit different levels of radiation absorption at different wavelengths of light. It has been observed *in vitro* experiments that up to about 600 *nm* the absorptions between Hb and HbO_2 are very similar, making it difficult to differentiate them. However, the absorption becomes much more differentiated from the wavelength of red light (about 650 *nm*) to the wavelength of infrared light (about 950 *nm*) [14, 16, 17]. Based on these fundamentals, the identifier was tested with each of the blood samples using yellow light (λ = 620 *nm*), orange (λ = 670 *nm*), red (λ = 750 *nm*) and infrared (λ = 850 *nm*). Figure 3 shows the results of these tests.

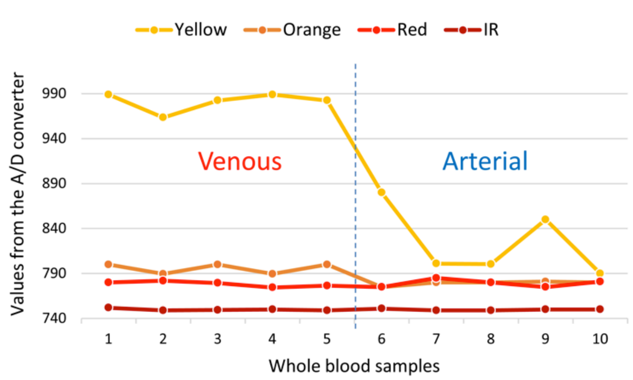

FIGURE 3. Digital values obtained by the A/D converter of the reflected light captured by the ROS of each wavelength incident on each blood sample. Left of the vertical dashed line is venous blood and the right of the line corresponds to arterial blood.

The first 5 samples correspond to venous blood and the remaining 5 to arterial blood. It can be observed that as the wavelength increases, the separation (in magnitude order) of the reflected light readings between the veins and arteries decreases. It can also be observed, for example, that the reflected yellow light is the one that could best discriminate between veins and arteries. This can also be seen in the statistics presented in Table 1.

TABLE 1. Central-tendency statistics of the results (i.e. decimal representation of the output binary values of the A/D converter) obtained from the ROS tests with 4 different wavelengths, applied to the 'in vitro' venous and arterial blood samples.

	Max	Min	Mean	S.D.	C.V.	Median
Venous (n = 5)						
Yellow	989	964	981	10	0.011	983
Orange	800	790	796	6	0.007	800
Red	782	775	779	3	0.004	780
IR	752	749	750	1	0.002	750
Arterial (n = 5)						
Yellow	880	790	824	39	0.047	801
Orange	781	775	779	2	0.003	780
Red	785	775	779	4	0.005	780
IR	751	749	750	1	0.001	750

Max = maximum value; Min = minimum value; S.D. = standard deviation; C.V. = coefficient of variation; IR = infrared.

If we compare, for example, the means or medians of each reflected light, it is seen that there is sufficient separation, in orders of magnitude, between veins and arteries corresponding to the yellow light and that as the wavelength increases, the separation, in orders of magnitude, of statistics between veins and arteries drastically decreases, making it difficult to discriminate. It is also noted that data dispersion, such as standard deviation and coefficient of variation, are higher in arterial blood than in venous blood for reflected yellow light.

In Vivo Test

Following the NOM-062-ZOO-1999 [18, 19], veterinarian surgeons performed an open surgery *in vivo* of pelvic abdominal type on a 5 years old male canine model. The identifier was tested using yellow (λ = 620 *nm*), orange (λ = 670 *nm*), red (λ = 750 *nm*) and infrared lights (λ = 850 *nm*) over 4 different blood vessels on the abdominal cavity of the canine model, previously identified by a veterinarian physician as veins (n = 2) and as arteries (n = 2). The surgeon placed the ROS of the identifier perpendicularly on the surface of each blood vessel (i.e. 2 veins and 2 arteries) and took readings for each reflected light color on 12 different points of the vessels. Therefore 2 vectors of 12 readings for veins and 2 vectors of 12 readings for arteries were obtained. Then, the 2 vein readout vectors and the 2 artery readout vectors were averaged separately to obtain a single data vector (n = 12) for vein and a single data vector (n = 12) for artery. It can be seen on the graphs in Figure 4 that the yellow and orange reflected lights follow a similar pattern, although it can be noticed that the orange light is the best to make the differentiation between veins and arteries.

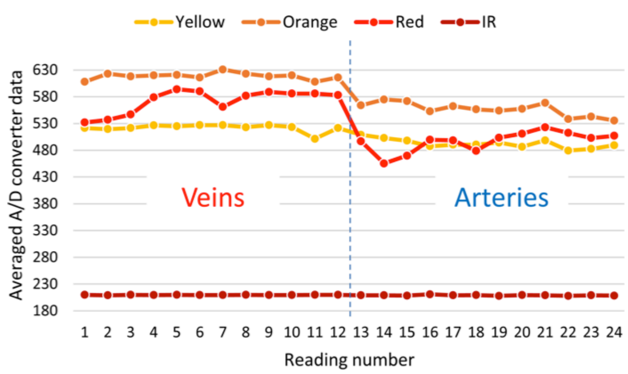

FIGURE 4. Averaged digital values obtained with the A/D converter of each reflected light from the blood vessels in the canine model, captured by the ROS. The left side of the vertical dashed line corresponds to venous blood and the right side to the arterial blood.

The statistics of these results, shown on Table 2, also show important differences that could be used to automatically differentiate a vein from an artery. For example, by establishing cutting points, thresholds or ranges between the minimum values of light reflected from the veins and the maximum values of light reflected from the arteries. This idea is explained in more detail in next section.

Automatic Detection

To differentiate between veins and arteries, it was decided to work with the orange light (λ = 670 *nm*), since this was the light that showed a wider range of values between the minimum value of the light reflected from the veins and the maximum value of the light reflected from the arteries without overlaps. In other words, in all cases of wavelengths tested, with exception of the orange light, local minimum values (Figure 4) or minimum mean values (Table 2) of light reflected from veins were sometimes observed as being below local maximum values or maximum mean values of light reflected from arteries (i.e. overlapping values), respectively. Conversely, local maximum values or maximum mean values of reflected light from arteries sometimes were above local minimum values or minimum mean values of light reflected from veins, respectively. These characteristics of the orange light allowed establishing a better margin to perform the automatic separation between veins and arteries. Figure 5 shows the thresholds (i.e. cutting points) established between the values zone corresponding to the veins and the ones that correspond to the arteries, estimated by using the following Equations:

$$CP_V = \bar{x}_V - 3\sigma_V \quad (1)$$

$$CP_A = \bar{x}_A + 3\sigma_A \quad (2)$$

Where:

CP_V = Cutoff point or threshold that defines the zone to classify a blood vessel as a vein.

CP_A = Cutoff point or threshold that defines the zone to classify the blood vessel as an artery.

$\bar{x}_V$ = Mean of the data vector of the reflected light by the veins, digitalized with the A/D converter.

$\bar{x}_A$ = Mean of the data vector of the reflected light by the arteries, digitalized with the A/D converter.

σ_V = The standard deviation of the data vector of the reflected light by the veins, digitalized with the A/D converter.

σ_A = The standard deviation of the data vector of the reflected light by the arteries, digitalized with the A/D converter.

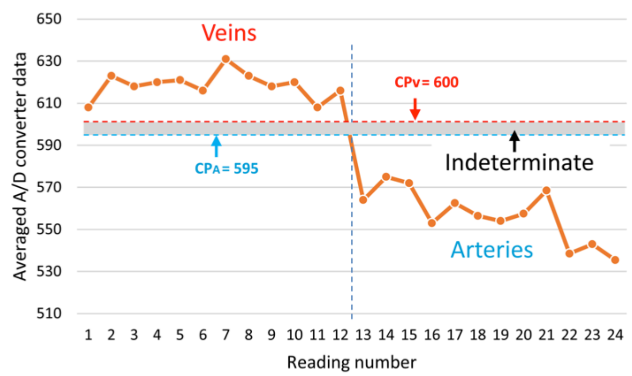

FIGURE 5. Cutting points (horizontal dashed lines) marking the regions for the classification of the veins and arteries, CP_V and CP_A, respectively. The shaded region between both CP is defined as indeterminate zone.

The means and medians of most of the values measured by the identifier from the different reflected wavelengths in the tests performed both *in vitro* (Table 1) and *in vivo* (Table 2) showed very similar values, therefore a good degree of symmetry can be assumed in the data distribution functions. Thus, the standard deviation in equation (1) and (2) is multiplied by a factor of 3 to prevent the probability that any future measurements performed by the identifier tend to deviate too far from the means.

TABLE 2. Central-tendency statistics of the results (i.e. decimal representation of the output binary values of the A/D converter) obtained from the ROS tests with 4 different wavelengths, applied to the 'in vivo' canine model.

	Max	Min	Mean	S.D.	C.V.	Median
Venous ($n = 12$)						
Yellow	527	502	522	7	0.013	523
Orange	631	608	619	6	0.010	619
Red	594	532	572	22	0.038	583
IR	210	209	210	0	0.002	210
Arterial ($n = 12$)						
Yellow	509	480	492	9	0.017	491
Orange	575	536	557	13	0.023	557
Red	523	456	497	19	0.039	501
IR	211	208	209	1	0.004	209

Max = maximum value; Min = minimum value; S.D. = standard deviation; C.V. = coefficient of variation; IR = infrared.

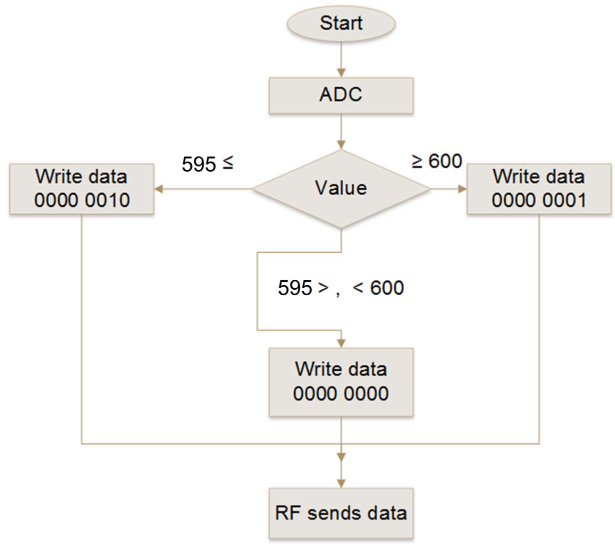

FIGURE 6. Flowchart describing the logic executed by the µC in the transmitter module. The photo-resistor voltage of the ROS is read by the ADC and assigned to an integer variable called "Value", which is compared with CP_V (i.e. 600) and CP_A (i.e. 595) thresholds. The result is written in an 8 bits register called "data" and sent to the receiver module via the radio frequency module.

This way, once the ROS picks up the reflected light from a blood vessel and inputs it to the µC, this processes the digitalized data by the A/D converter through an algorithm programmed in C++ and decides if the reflected light comes from a vein or from an artery, following the flowchart and conditions shown on Figure 6 and Table 3, respectively.

TABLE 3. Reading conditions.

Condition	Assigns	Identified as
If A/D value ≥ 600	00000001	Vein
If $595 <$ A/D value < 600	00000000	Indeterminate
If A/D value ≤ 595	00000010	Artery

In other words, if the A/D value delivered to the µC is equal or greater than the CPV threshold (i.e. 600) then the binary number 1 is sent through the RFT transmitter to the receiver module. The µC of the receiver module, also programmed in C++, once received the binary number, executes the algorithm following the flowchart and response decision shown on Figure 7 and Table 4, respectively, activating the buzzer with an audible frequency of 280 *Hz* and turning on the red color of the RGB LED to alert the surgeon and medical staff that a vein has been detected. If the A/D value is equal or lower than the CPA threshold (i.e. 595) then the binary number 2 is sent to the receiver module. Then, the µC of the receiver after receiving the binary number 2 executes the response conditions by activating the buzzer with an audible frequency of 1600 *Hz* and turning on the blue of the RGB LED, to alert the surgeon and medical staff that an artery has been detected. If the A/D value reaching

TABLE 4. Response conditions.

Binary Number	Condition	Buzzer	RGB LED
00000001	If data ==	280 *Hz*	Red
00000000	If data ==	Indeterminate	Green
00000010	If data ==	1600 *Hz*	Blue

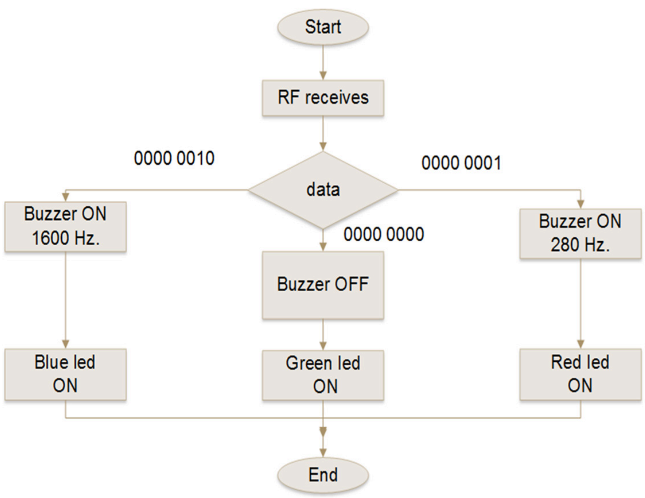

FIGURE 7. Flowchart describing the logic that executes the µC of the receiver module. When the RF module receives the discrimination value from the RF transmitter, it passes it to the microcontroller which writes it to a variable called "data". Then it compares it with three different values stored in registers of 8 bits and depending on it activates the PWM outputs to turn on the buzzer or the digital outputs to turn on the LED, as the case may be.

the receiver module is higher than 595 or lower than 600, then there is no sound and only the RGB LED green is on, informing the surgeon and medical staff that it was unable to identify the blood vessel as either a vein or an artery. Sound or visual warning to the surgeon and his assistants, on the identification of the blood vessel, is with the intention that the most experienced of the medical team can help in the confirmation of the identification of the blood vessel; the less experienced can be trained and the students learn. The full identifier device is shown in Figure 8.

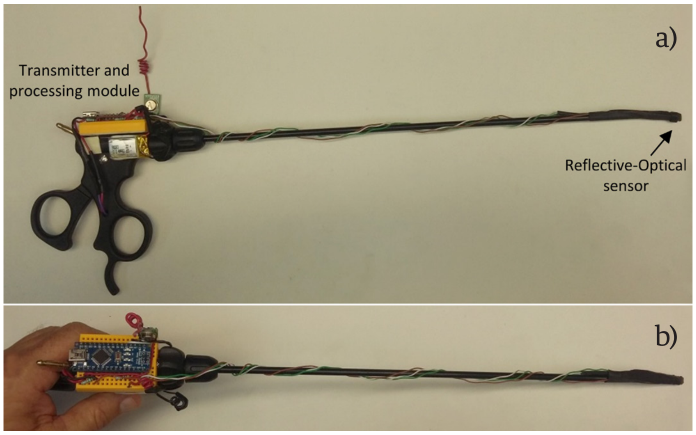

FIGURE 8. Panoramic view of (A) the lateral and (B) top of the laparoscopic device.

In this research work, 4 light wavelengths emitted by the identifier's ROS were tested, aiming them to hit over different *in vitro* and *in vivo* blood samples, with the purpose of observing the reflective responses and assess the feasibility for them of being used to discriminate between venous and arterial blood. The *in vitro* tests showed that both yellow and orange lights (i.e. $\lambda = 620$ *nm* and $\lambda = 670$ *nm*, respectively) deliver a good discriminatory response, although the tests were performed using non-pulsatile arterial blood and by controlling the interference of the surrounding light (i.e. noise).

On the other hand, the *in vivo* tests showed that the best wavelength to differentiate veins from arteries was the orange light (i.e. $\lambda = 670$ *nm*), even without controlling other surrounding light sources (i.e. noise) in the surgical room. Once the reading and response conditions were programmed into the identifier, this was blindly tested on different arteries in the canine model, without generating any erroneous identification of veins or arteries. The proposed identifier should be tested in other specimens *in vivo* in laparoscopic surgeries for better validation. The behavior of different identifier's ROSs (i.e. different wavelengths of light) should also be studied when exposed to the light sources during laparoscopic surgeries *in vivo*. These experiments are contemplated to be carried out in future works.

The veins and arteries identifier prototype is under experimentation and still has several practical limitations. Normally, 3 or 4 incisions are performed in laparoscopic surgery where the ports are inserted, which are used to channel the different surgical instruments. Sometimes it is necessary to exchange instruments through the ports, so up to now the prototype is intended for the surgeon to use it every time he hesitates if what he tries to cut is a vein or an artery. For now, the surgeon would have to decide whether to give a higher priority of use to the identifier, and dedicate one of the ports only for the manipulation of the identifier. Otherwise, the surgeon would have to be alternating between the use of the identifier and other laparoscopic instruments whenever he deemed it necessary. Other important aspects are the protection and sterilization of the identifier. All electronic circuitry must be encapsulated in such a way that they must be immune to possible spills of liquids, gases or bodily fluids; but should also allow sterilization using conventional methods such as ethylene oxide, hydrogen peroxide, or glutaraldehyde.

CONCLUSION

We were able to prove that with an economic and simple reflective-optical sensor adapted to a conventional laparoscopy device, it is possible to differentiate between venous and arterial blood vessels, which would assist the practice of minimally invasive surgeries.

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