Journal of Medical Systems (2019) 43: 316
https://doi.org/10.1007/s10916-019-1447-6

PATIENT FACING SYSTEMS

Non-Invasive Method to Estimate Red Blood Cell in Blood

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Received: 4 July 2019 / Accepted: 29 August 2019 / Published online: 10 September 2019

Abstract

This work proposes a non-invasive method to estimate the number of red blood cells in the blood. To achieve the development of this research, first, a photosensitive device was designed, which is formed by a phototransistor with a transparent casing allowing the red light coming from a red LED to penetrate the sensor. This means, that when the intensity of the light varies, the amount of current flowing through the sensor also changes. In consequence, this variation in electric current causes a variation on the voltage drop across the connections of a resistor, which is read by a microcontroller that calculates the number of red blood cells. Second, some formulas were established to represent the relationship between the extreme points of a data set obtained during a sampling process. Finally, to verify the device operation, a sampling process was performed in volunteer patients (range 18–84 years) with venous blood samples run on a laboratory hematology analyzer, a total 68 measurements were made to people of different ages and genders, of which 34 are females and 34 are males.

Keywords Red blood cells · Microcontroller · Phototransistor · red LED · Sensors · Voltage

Introduction

Usually, anemia occurs when there is an alteration in the blood composition, this is because the body does not produce enough red blood cells, and as a consequence, it decreases the Hemoglobin (Hb) and Hematocrit (Hct) level. Also, another important effect of anemia is that it decreases the oxygen transport capacity of the blood, therefore, the oxygen supply to various organs also decreases [1]. In this sense, the red blood cell count is essential to detect different diseases, such as anemia, leukemia, among others. This information is of vital importance to detect and diagnose illnesses in time, and in this way, provide the appropriate treatment.

The beginning of the methods or techniques for counting the elements that form the blood was in 1658, when Jan Swammerdam first observed under a microscope, and the Red Blood Cell (RBC) count was performed in 1852 by Professor Karl Vierordt [2]. The first devices whose objective was to measure the thickness of the blood based on its opacity began to appear around that time. According to the Leukemia & Lymphoma Society [3], the normal range for the number of red blood cells in men is between 4.7 and 6.1 million cells per microliter. Similarly, the normal range for the number of red blood cells in women encompasses from 4.2 to 5.4 million cells per microliter. The red blood cell count is essential to detect different diseases, such as anemia, leukemia, among others. The current method used in clinical laboratories to process blood samples and obtain the cell analysis report is done through an automatic hematology analyzer, which is generally a machine of a very high price.

Some authors proposed the automatic blood cells counting using techniques of digital image processing, through some preprocessing and post-processing techniques in the image [4], and using plane extraction and counting techniques to

This article is part of the Topical Collection on *Patient Facing Systems*

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improve the results [5]. In this sense, a non-invasive device is proposed to estimate the number of red blood cells in the blood. It is based on the amount of light passing through the patient's index finger. The red blood cell count is very important because it helps to detect some diseases such as anemia, leukemia, patients with nutritional deficiencies or even pregnant women. The red blood cell count is performed for different reasons, mainly to control overall health and detect various disorders in time. Also, to diagnose and control disease, and to supervise some medical treatment in case the patient is taking medication that affects the red blood cell count.

This paper is structured as followed: section two presents the related research works, section three describes the materials and methods used to develop this project and the general procedure for calculating red blood cells is described; section four presents the data analysis; section five shows the overall results, and finally, section six presents the conclusions and future works to improve the proposed device.

Related research works

Nowadays, there are many kinds of research related to the red blood cell count using different methods. Some authors proposed the automated RBC count in a microscopic image using the Hough transform [6–9]. The authors [10] proposed a system based on the radon transform to automated marker identification in grey-scale images obtained by optical light microscopy of blood smears. In [11] a review of the different methodologies used for the counting of blood cells through the segmentation of images was presented. In this research, the authors described different techniques for processing images such as filtering, histogram equalization, thresholds, masking, morphological operations, and contrast enhancement, among others.

Recently, Christy et al. [12] have presented a system to classify the blood cell count through the blood smear using microscopic images with high-resolution cameras, to perform image processing using different techniques (grayscale conversion, image enhancement, contrast stretching, histogram equalization, thresholds). In another research work, Acharya et al. [13, 14] have proposed the technique of image processing to carry out the red blood cell count through the blood smear using the labeling algorithm and circular Hough transform, according to the results, better results are obtained with the circular Hough transform. According to related research works, Table 1 shows different works with image processing to perform the red blood cell count, the technique used, the process and the accuracy obtained with each method are specified. As can be seen in Table 1, the accuracy percentage obtained in each of the techniques used is presented. In this case, the Gray Threshold technique obtains the highest accuracy with 94.58%.

Below in Table 2, a comparative table of invasive and non-invasive methods is shown, the blood cell count with conventional methods is very laborious and time-consuming, in addition, some errors in cell concentration may occur due to human perception.

In case of automated cell counting methods, some devices whose main feature is portability have been developed, moreover, it allows faster measurements, guarantee high accuracy for cell counting and avoid human errors. However, there are some limitations for these automated devices such as the need to draw blood, they require a time-consuming to obtain results, or the inability to perform continuous monitoring. The MTX device is portable and can analyze 16 different bio-parameters in a short time, but the main disadvantage is that device does not have an affordable price, it is very expensive (approximately 2000 dollars). In this sense, a non-invasive method is proposed to estimate the number of red blood cells in the blood. Besides, this device can be used to make a faster diagnosis when dealing with a large population. Since that is a higher cell density, in this case, red blood cells will reduce the amount of light coming through a person's finger, a photosensitive sensor will, in consequence, be less stimulated resulting in a lower voltage at its output. Conversely, if the sensor is

Table 1 Image processing based counting of RBCs

Techniques	Process	Accuracy
Gray Threshold [15]	Input image, RGB to a gray conversion, median filtering, gray thresholding, filling of Holes, removal of borders, image labeling, form factor calculation, detection of cells, counting of cells.	94.58%
Circular Hough Transform [6]	Input image, crop sub-image, convert RGB to grayscale, morphology process, convert to a binary image, clear the border image, measure the minimum and maximum radius.	91.87%
The ABCCS method [16]	Blood sample acquisition, image processing, noise removal, median filter, edge detection, morphological filling, boundary detection, and counting.	91%
Circular Hough transform and thresholding [17]	Image acquisition, image enhancement, image segmentation, image labeling, detection and counting, cells count.	93.1%

Table 2 Invasive and non-invasive methods

Invasive methods	Non-invasive methods
• Hemocytometer or also called a Petroff-Hausser slide is a method used to calculate the cell density of a blood sample using a microscope [18]. • NucleoCounter is an automatic cell counter using image cytometry to perform image analysis in three steps: 1) take a sample, 2) load sample, and 3) run sample for automated results. It has several versions such as YC-100, SP-100, NC-200, and NC-3000 [19]. • Hematology analyzers are usually large devices, the use of which is generally restricted to centralized laboratories. These analyzers are mainly used for cell counts and differential leukocyte analysis, are based on different technologies, such as electrical impedance, radiofrequency conductivity, light scatter, fluorescent scatter, and cytochemistry [20].	• Surface Charge of Blood Cells is an approach based on electrical properties of blood cells, using the zeta potential to measure blood components [21]. • SpHb monitoring is a technological device that allows continuous evaluation in real-time of changes in Hb levels [22]. • MTX Device is a non-invasive device that measures several biological parameters without the need to draw blood [23].

stimulated by a higher amount of light, the result will be a higher voltage level at its output. This photosensitive device consists of a phototransistor with a transparent casing. A transparent casing will allow the red light coming from a red LED to penetrate the sensor.

Material and methods

During the development of this project, it was necessary to implement some steps to obtain the estimation of red blood cells. First, the internal circuit design was made and the required components were welded, second, the final design related to the construction of the circuit board is proposed, and third, once the device was finished, the sampling process was performed with male and female patients of different ages, at the same time and under the same conditions. The next step was to analyze the data and compare both results. Finally, the software was designed and the equations developed during the data analysis have been evaluated and compared with the data obtained in the sampling process.

Internal circuit design

The internal circuit design is composed of four parts: a) a photosensitive element and a red LED, b) an amplifier stage for the signal that comes from the phototransistor, c) a circuit whose work is to adjust the voltage signal to a level that is compatible with a microcontroller and the last parts d) a digital circuit whose work is the processing of the voltage signal and control of an LCD display. Adjoined to this stage are all the necessary elements that help the microcontroller to work properly. These elements are a quartz crystal resonator, two ceramic capacitors, pull-up resistors for the reset pin and other buttons. Finally, the whole circuitry is fed by a voltage regulating stage that delivers the necessary voltage levels for each stage of the device.

It should be noted that the red LED is mainly used because the red wavelength of 660 nM is easily absorbed by the blood cells of interest, in this case, the red blood cells. Therefore, the element that produces the light that will pass through the finger is composed of a light-emitting diode. This diode is forward biased through a resistor. This resistor ensures the LED to work within the safe current ranges while granting the maximum level of brightness. The current that circulates through the diode is given by the following equation:

$$I_{LED} = \frac{V_s - V_{LED}}{R_{LED}} \quad (1)$$

where I_{LED} denotes the current flowing through the series circuit formed by the resistor and the LED. V_S indicates the voltage of the power source, V_{LED} represents the voltage drop through the LED, and R_{LED} designates the resistor in series with the LED.

$$I_{LED} = \frac{8V - 1.8V}{330\Omega} = 18.7mA \quad (2)$$

The maximum current intensity for a common red LED is 20 mA. The brightness increment according to the current, but it should be taken into account the maximum current that a given LED can withstand. The amplifier circuit mentioned above helps increase the current coming out from the photosensitive sensor. This task is accomplished by a general-purpose NPN transistor. Concerning the microcontroller has 13 general input/output ports. Six of these ports can be configured as PWM signal outputs. Besides, the device incorporates a UART port and a six-channel analog to digital converter [24]. The device operates under the range from 3.3 V to 5 V. Last, it possesses a 32 KB flash memory for storing programs and a 2 KB EEPROM. On Fig. 1 it is shown the description labels for each one of the pins on an ATMEGA328P microcontroller and their use on an Arduino board, in this case, an Arduino UNO board.

Final design

This step involves the construction of the circuit board as well as the choosing of an outer casing for the device. For the printed circuit board, a factory holed, with a track distribution similar to a prototype board, the printed circuit board was used. The optical receptacle used for taking in the index finger is made of a PVC coupling pipe with three openings. The placement of the optical elements inside the PVC coupling must be done in such a way that the maximum amount of light can be caught by the phototransistor. This means the phototransistor is placed in front of the LED, the source of light. This space will be occupied by the patient's finger at the moment of the sampling. Given the fact that these optical elements must remain fixed at all moments, two cork caps were used for this task. They were drilled in the middle with adequate size for the optical elements. Once having assembled the whole internal circuitry alongside the required wiring for the other components, it is needed to place all these objects inside a plastic casing. This way the device will be ready to begin the sampling process. Figure 2 depicts the final facade of the device.

Sampling process

In order to create a program for the device, data must be obtained and processed. Therefore, blood biometry was performed in the laboratory and measurements were made with

Fig. 2 Final design of the red blood cell estimator

the device to estimate the number of red blood cells and compare both results.

The first part involves the retrieval of laboratory test results in relation to the amount of voltage measured by the semi-quantitative estimator of red blood cells (see Fig. 3). Initially, the device was programmed to show the voltage signal coming from the amplifier stage. A list of 68 people from different ages and genre was made, 34 people are females and 34 are males. This list also showed the specific voltage drop for each person in particular. The laboratory test that contained the data of interest, in this case, the number of red cells per microliter is called hematic biometry.

Software design to calculate the red blood cells

The next step consists of the creation of an Arduino program that allows the microcontroller ATMEGA328P to calculate an approximate of the number of red blood cells based on the voltage levels it is acquiring through its analog input. Figure 4 shows the general procedure for calculating red blood cells and exemplifies the software operation.

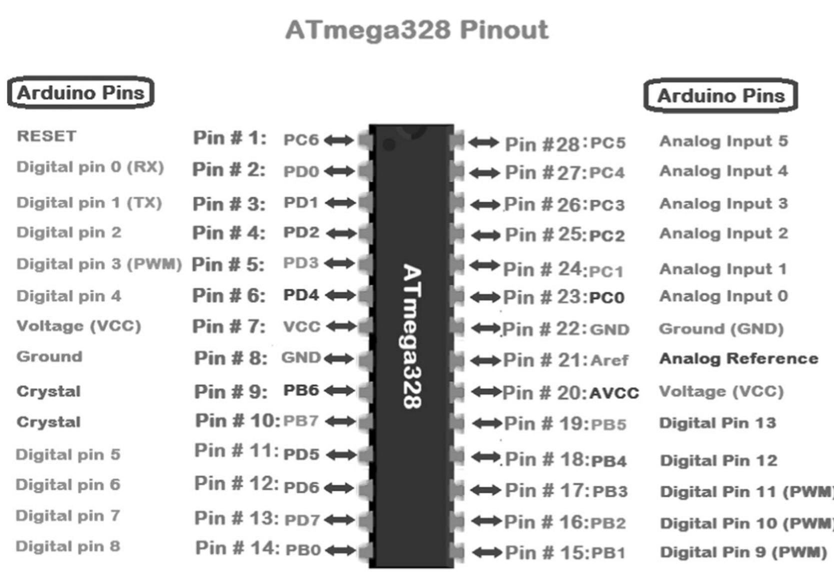


Fig. 1 Description of pins on an ATMEGA328P microcontroller for an Arduino board

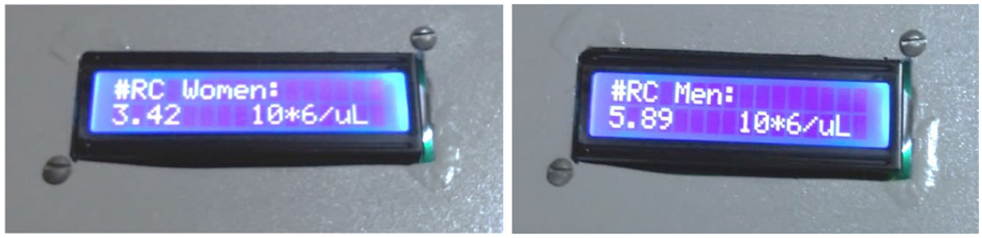


Fig. 3 Measurements through the semi-quantitative estimator of red blood cells

According to Fig. 4, first off, the microcontroller executes a reading operation of the voltage seen at its pin A5 (analog input). After that, the microcontroller executes a scanning operation to determine the state of the pin where the "Select Gender" switch is located. That is, if the person who is going to undertake the reading is a woman, then the switch must be put in the open position. Therefore, a high state will be read. With that, depending on the voltage level measured from the optic sensor, the following messages will be displayed on the LCD (see Fig. 5): if there is no finger placed inside the receptacle, an "Insert Finger" message will be shown, if the reading operation is zero because there is a total blockage on the photosensitive sensor, a "Wrong Reading" message will be displayed and if the former two conditions are not satisfied, then the microcontroller will proceed with the calculation of the amount of RBC.

Data analysis

After having finished the sampling process, the new task at hand involved the creation of a set of equations that satisfy the relationship between the number of red blood cells and the voltage obtained for each one of the individuals involved in the sampling process. Table 3, it is shown the relationship between the number of red blood cells and the level of voltage measured with the device for female patients:

Similarly, Table 4 shows the relationship between the number of red blood cells and the voltage level measured with the device for male patients:

Hemoglobin is the main component of red blood cells, and its function is to transport of oxygen from the lungs to the tissue [25]. In this sense, Fig. 6 shows the relationship between the amount of hemoglobin and red blood cells

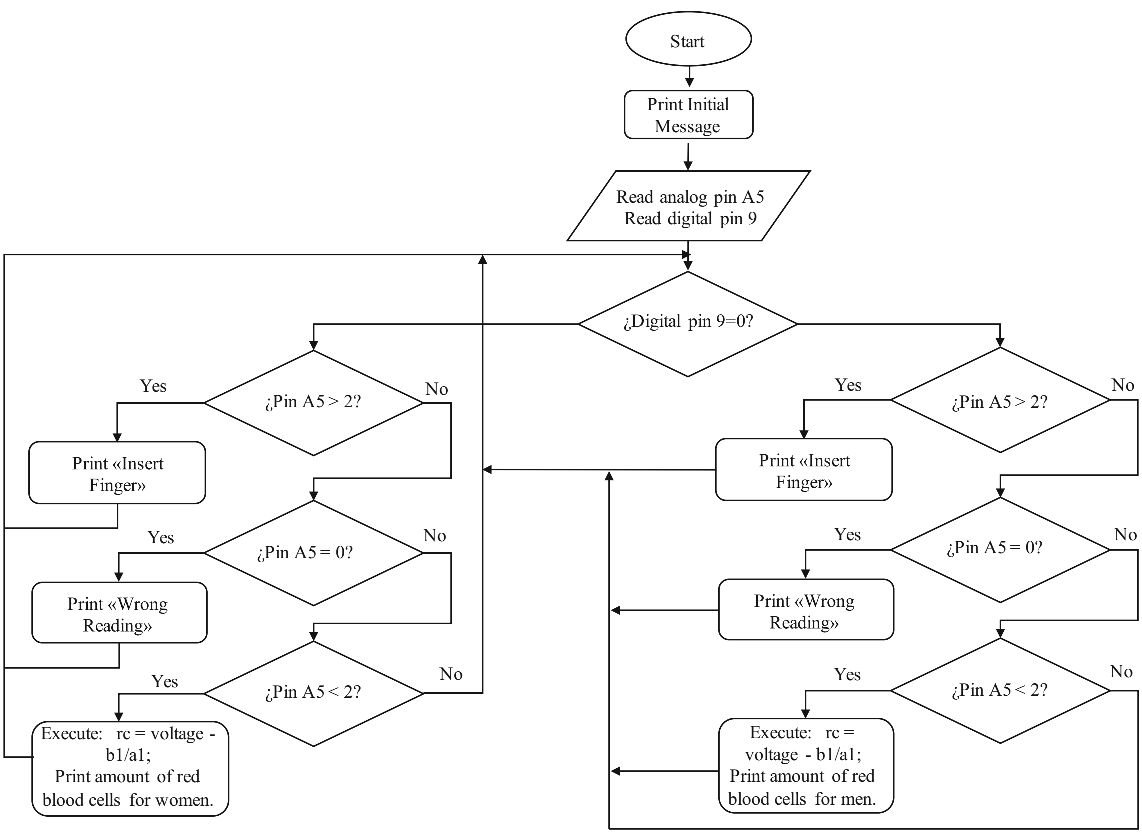


Fig. 4 Flow chart depicting the operation of the software for the microcontroller

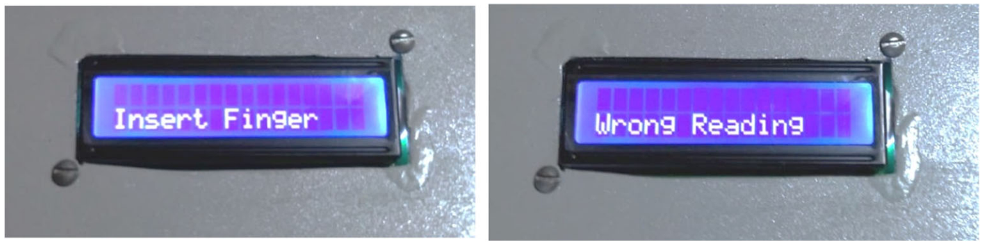


Fig. 5 Informational messages displayed on the LCD, to know the status of the measurement

(according to the information in Tables 1 and 2), it can be seen that there is a linear relationship between the two basic parameters of hematic biometry. Concerning the voltage as a function of red blood cells, a general tendency can be observed that shows a decrease in the amount of voltage when the number of red blood cells increases.

Table 3 The relationship among hemoglobin levels, the number of red cells, voltage, and age of the female patients

Person	Gender	Age	Hemoglobin	# Red cells	Voltage
1	F	77	12.5	$4.39 x 10^6/\mu L$	0.14 V
2	F	25	10.3	$3.43 x 10^6/\mu L$	0.83 V
3	F	84	12.8	$4.54 x 10^6/\mu L$	0.43 V
4	F	18	10.4	$3.70x 10^6/\mu L$	0.31 V
5	F	68	11.4	$3.86 x 10^6/\mu L$	0.14 V
6	F	55	13.1	$4.77 x 10^6/\mu L$	0.63 V
7	F	36	10.5	$3.75 x 10^6/\mu L$	0.20 V
8	F	59	13.3	$4.71 x 10^6/\mu L$	0.31 V
9	F	18	11.9	$4.13 x 10^6/\mu L$	0.37 V
10	F	21	13.1	$5.05 x 10^6/\mu L$	0.66 V
11	F	20	8.80	$2.91 x 10^6/\mu L$	0.40 V
12	F	40	12.6	$4.30 x 10^6/\mu L$	1.20 V
13	F	23	10.9	$3.71 x 10^6/\mu L$	0.43 V
14	F	29	11.6	$4.05 x 10^6/\mu L$	0.84 V
15	F	42	12.4	$4.29 x 10^6/\mu L$	0.89 V
16	F	54	11.8	$4.09 x 10^6/\mu L$	0.40 V
17	F	19	11.1	$3.88 x 10^6/\mu L$	0.30 V
18	F	22	8.60	$2.90 x 10^6/\mu L$	0.38 V
19	F	55	12.1	$4.32 x 10^6/\mu L$	0.40 V
20	F	33	11.9	$4.05 x 10^6/\mu L$	0.52 V
21	F	18	10.1	$3.55 x 10^6/\mu L$	0.17 V
22	F	28	11.0	$3.82 x 10^6/\mu L$	0.26 V
23	F	71	15.6	$5.89 x 10^6/\mu L$	0.31 V
24	F	22	11.6	$3.92 x 10^6/\mu L$	0.49 V
25	F	28	13.4	$5.26 x 10^6/\mu L$	0.23 V
26	F	31	11.2	$3.65 x 10^6/\mu L$	0.60 V
27	F	25	10.1	$4.39 x 10^6/\mu L$	0.40 V
28	F	46	10.5	$3.86 x 10^6/\mu L$	0.49 V
29	F	66	12.4	$4.4 x 10^6/\mu L$	0.31 V
30	F	23	11.2	$3.86 x 10^6/\mu L$	0.37 V
31	F	20	10.20	$3.86 x 10^6/\mu L$	0.40 V
32	F	60	13.2	$5.08 x 10^6/\mu L$	0.17 V
33	F	57	12.0	$4.25 x 10^6/\mu L$	0.26 V
34	F	68	11.9	$3.95x 10^6/\mu L$	0.31 V

Table 4 The relationship among hemoglobin levels, the number of red cells, voltage, and age of the male patients

Person	Gender	Age	Hemoglobin	# Red cells	Voltage
1	M	73	13.4	$4.65 x 10^6/\mu L$	0.23 V
2	M	43	11.7	$4.20 x 10^6/\mu L$	0.29 V
3	M	29	15.8	$5.73 x 10^6/\mu L$	0.29 V
4	M	57	14.0	$5.15 x 10^6/\mu L$	0.29 V
5	M	37	16.2	$5.73 x 10^6/\mu L$	0.14 V
6	M	18	17.2	$6.11 x 10^6/\mu L$	0.11 V
7	M	84	11.1	$4.05 x 10^6/\mu L$	0.43 V
8	M	49	10.6	$3.55 x 10^6/\mu L$	0.40 V
9	M	80	12.9	$4.46 x 10^6/\mu L$	0.14 V
10	M	52	11.5	$4.24 x 10^6/\mu L$	0.43 V
11	M	30	13.0	$5.10 x 10^6/\mu L$	0.27 V
12	M	70	12.9	$4.64 x 10^6/\mu L$	0.23 V
13	M	39	11.7	$4.20 x 10^6/\mu L$	0.20 V
14	M	50	12.0	$4.16 x 10^6/\mu L$	0.40 V
15	M	27	13.0	$5.12 x 10^6/\mu L$	0.16 V
16	M	76	11.0	$3.54 x 10^6/\mu L$	0.14 V
17	M	58	14.3	$4.20 x 10^6/\mu L$	0.37 V
18	M	21	10.9	$4.15 x 10^6/\mu L$	0.44 V
19	M	47	13.9	$5.15 x 10^6/\mu L$	0.25 V
20	M	36	15.5	$5.31 x 10^6/\mu L$	0.18 V
21	M	63	11.1	$3.82 x 10^6/\mu L$	0.37 V
22	M	26	14.1	$5.22 x 10^6/\mu L$	0.21 V
23	M	71	13.2	$4.89 x 10^6/\mu L$	0.24 V
24	M	38	16.4	$6.05 x 10^6/\mu L$	0.12 V
25	M	45	10.2	$3.42 x 10^6/\mu L$	0.43 V
26	M	30	15.7	$5.41 x 10^6/\mu L$	0.23 V
27	M	58	11.0	$3.86 x 10^6/\mu L$	0.35 V
28	M	20	15.2	$5.12 x 10^6/\mu L$	0.14 V
29	M	72	13.5	$4.92 x 10^6/\mu L$	0.21 V
30	M	19	16.1	$6.10 x 10^6/\mu L$	0.11 V
31	M	25	11.2	$3.92 x 10^6/\mu L$	0.36 V
32	M	47	14.8	$5.32 x 10^6/\mu L$	0.23 V
33	M	36	11.5	$4.11x 10^6/\mu L$	0.32 V
34	M	52	15.3	$5.82 x 10^6/\mu L$	0.23 V

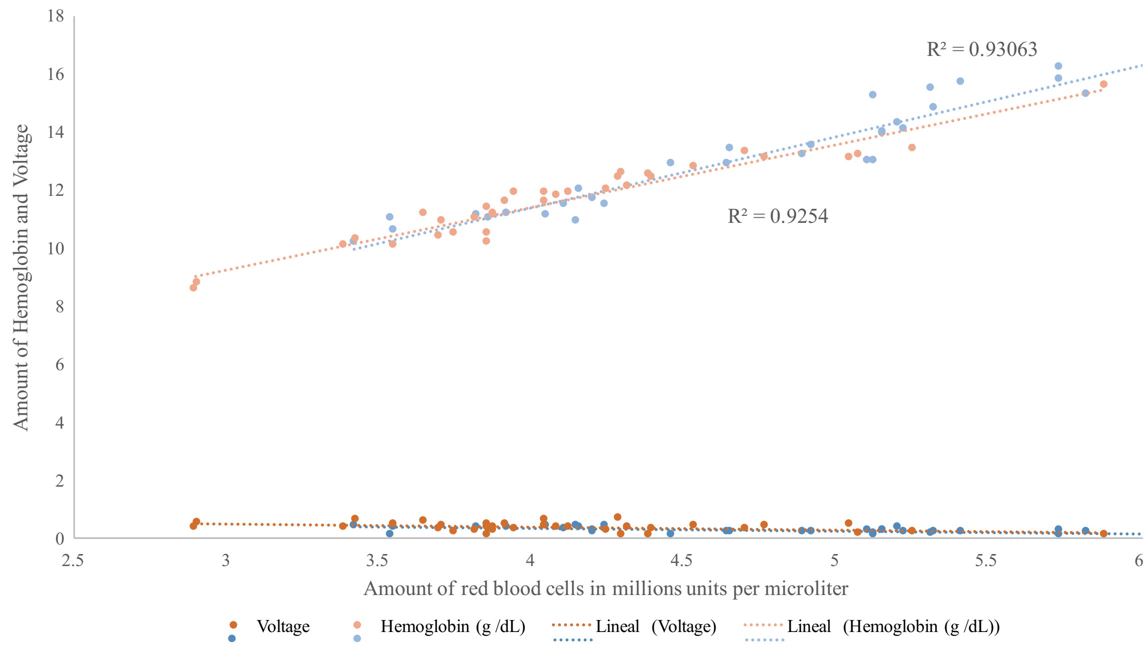


Fig. 6 Hemoglobin and voltage depending on the number of red blood cells for male and female patients

Figure 7, it is shown the percentage amounts of the female and male population falling on different ranges expressed in millions of red blood cells per microliter. Based on those percentage amounts shown above, it is possible to determine which part of the population falls within a specific blood cell range. In reference to Fig. 7, where the percentage amounts for the female population are located, it is observed that 50% of them fall within the 3 to 4 million of red blood cells per micro liter range. In contrast to that, the higher percentage for the male population falls within the range from 4 to 5 million red blood cells per microliter.

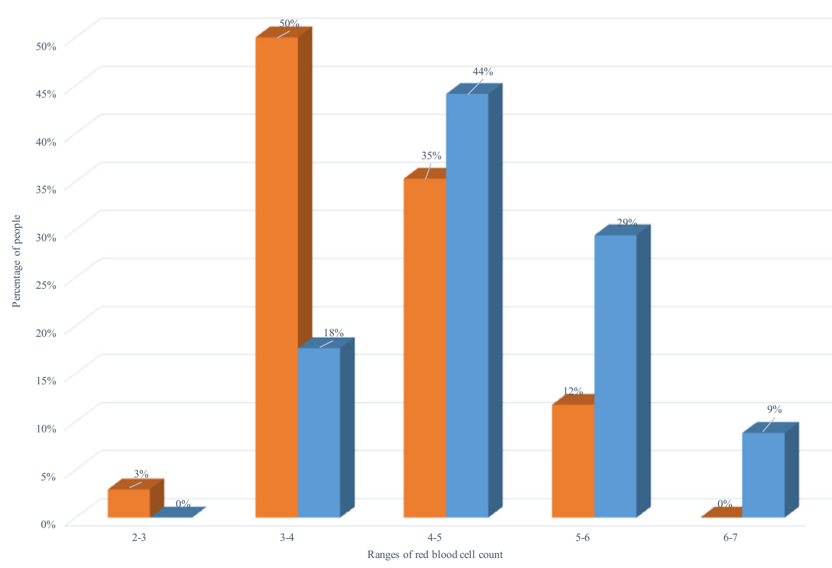
These percentages will serve to set the required parameters to fit a straight line that will allow for the calculation, at a certain extent, of a number of red blood cells within a specific range. Definite extreme points for the male and female populations will serve for this purpose. In this sense, for the case of the female population, these points are: 3.86 million red blood cells per microliter at 0.14 V and 3.43 million red blood cells per microliter at 0.83 V. Thus, the coordinates are (3.86, 0.14) and (3.43, 0.83). According to the formula used to find the inclination of a straight line, it is stated that:

$$m = \frac{y_2 - y_1}{x_2 - x_1} \quad (3)$$

If $y_2 = 0.14$, $y_1 = 0.83$, $x_2 = 3.86$ and $x_1 = 3.43$; the inclination for this line is:

$$m = \frac{y_2 - y_1}{x_2 - x_1} = \frac{0.14 - 0.83}{3.86 - 3.43} = -1.604 \quad (4)$$

Fig. 7 Percentage amounts of the female and male population falling on different ranges of the number of blood cells



The general form for a straight line equation is:

$$y = mx + b \tag{5}$$

Finally, the straight line equation that relates the number of red blood cells with voltage level in females is:

$$y = -1.604x + 6.14 \tag{6}$$

For the male population, the following extreme points were located: 6.11 millions of red blood cells per microliter at 0.11 V and 3.45 millions of red blood cells per microliter of blood at 0.43 V. The final coordinates are: (6.11, 0.11) and (3.45, 0.43). Using the aforementioned formula to find the inclination of a straight line, it is found that:

$$m = \frac{y_2 - y_1}{x_2 - x_1} = \frac{0.11 - 0.43}{6.11 - 3.45} = -0.120 \tag{7}$$

Finally, the straight line equation that relates the amount of red blood cells with voltage levels is:

$$y = -\,0.120x + 0.85 \tag{8}$$

Evaluation of the equations

Finally, an evaluation process was undertaken. For this, those equations developed in the data analysis step were tested using some values of voltage presented in Table 1 for male patients and Table 2 for female patients. The values chosen for this step had to be within the range of red blood cells for which these equations were created. For women falling within the range 3 to 4, the equation is:

$$x = \frac{(y - 6.14)}{-1.604} \tag{9}$$

For the male population, the range is 4 to 5, and the required formula is:

$$x = \frac{(y - 0.85)}{-0.120} \tag{10}$$

where, for both equations: x = amount of red blood cells and y = voltage level.

Results

Once the equations are evaluated, the final action involves the comparison between the data obtained with laboratory tests and the results given by the evaluated equations. On Table 5, it is shown a list with the number of red blood cells per microliter of 20 different patients. The first column corresponds to female patients and the second column to male patients. For each column, the results of the laboratory tests, the result obtained by the device, and the accuracy obtained with the device in relation to laboratory measurements are presented. The accuracy of device was obtained by calculating the Squared Error (SE) in each of the measurements, considering the error as the difference of the real laboratory result and the estimated measurement of the device (SE = $(real - estimate)^2$), then, the Mean Squared Error (MSE) was obtained using the following equation:

$$MSE = \frac{1}{N} \sum_{i=1}^{N} real_i - estimate_i \tag{11}$$

where N is the total number of measurements. Also, the Pearson correlation coefficient was used to quantify the relationship between the two variables ($X = \#Red\ Cells$ and $Y = Hemoglobin\ (g/dL)$). According to the results, in Fig. 6 it can be seen that the points are located very close to the line, indicating that there is a strong relationship in the variables. In the case of male patients a large positive relationship is obtained: Pearson R = 0.93063, similarly in female patients a large positive relationship is obtained: Pearson R = 0.9254.

Table 5 The relationship between the number of red blood cells obtained in the laboratory and on the device

Women			Men		
Laboratory	Device	Accuracy	Laboratory	Device	Accuracy
$4.26\ x\ 10^6/\mu L$	$3.63\ x\ 10^6/\mu L$	99.60%	$6.11\ x\ 10^6/\mu L$	$6.16\ x\ 10^6/\mu L$	99.99%
$4.19\ x\ 10^6/\mu L$	$3.57\ x\ 10^6/\mu L$	99.61%	$5.33\ x\ 10^6/\mu L$	$4.66\ x\ 10^6/\mu L$	99.55%
$4.18\ x\ 10^6/\mu L$	$3.57\ x\ 10^6/\mu L$	99.62%	$5.3\ x\ 10^6/\mu L$	$4.83\ x\ 10^6/\mu L$	99.77%
$4.06\ x\ 10^6/\mu L$	$3.59\ x\ 10^6/\mu L$	99.77%	$5.12\ x\ 10^6/\mu L$	$5.75\ x\ 10^6/\mu L$	99.60%
$3.95\ x\ 10^6/\mu L$	$3.63\ x\ 10^6/\mu L$	99.89%	$4.65\ x\ 10^6/\mu L$	$5.16x\ 10^6/\mu L$	99.73%
$3.92\ x\ 10^6/\mu L$	$3.52\ x\ 10^6/\mu L$	99.84%	$4.64\ x\ 10^6/\mu L$	$5.16\ x\ 10^6/\mu L$	99.72%
$3.7\ x\ 10^6/\mu L$	$3.63\ x\ 10^6/\mu L$	99.99%	$4.59\ x\ 10^6/\mu L$	$4.0\ x\ 10^6/\mu L$	99.65%
$4.65\ x\ 10^6/\mu L$	$3.45\ x\ 10^6/\mu L$	98.56%	$4.16\ x\ 10^6/\mu L$	$3.75\ x\ 10^6/\mu L$	99.83%
$3.44\ x\ 10^6/\mu L$	$3.64\ x\ 10^6/\mu L$	99.96%	$3.55\ x\ 10^6/\mu L$	$3.75\ x\ 10^6/\mu L$	99.96%
$3.31\ x\ 10^6/\mu L$	$3.59\ x\ 10^6/\mu L$	99.92%	$3.45\ x\ 10^6/\mu L$	$3.5\ x\ 10^6/\mu L$	99.99%

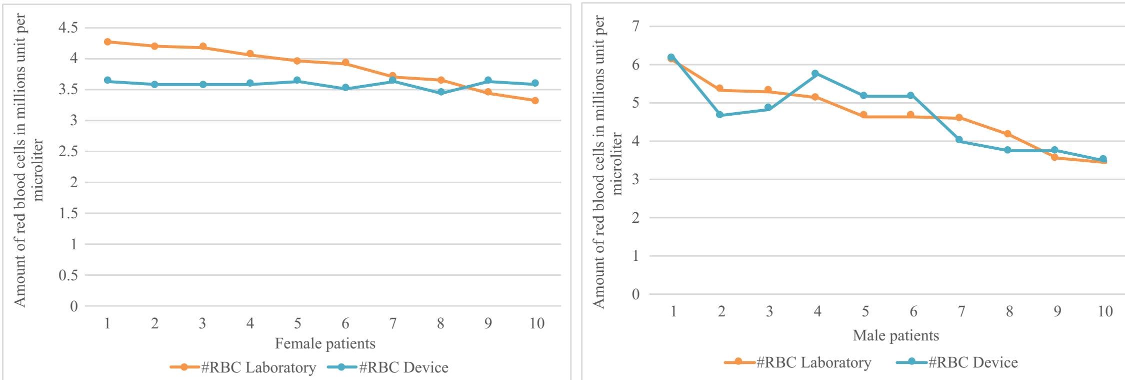


Fig. 8 Results of laboratory tests and measurements calculated by the device for female and male patients

As it can be appreciated in Fig. 8, there are variations between the results given by the laboratory tests and the amounts that would be calculated by the device. However, this is to be expected since it is a non-invasive device that relies on optic sensors. Variations in light intensity due to physical traits such as nail thickness, finger thickness, nail polish and the amount of pressure exerted by the person on the sensor will cause a change in the results.

In spite of all the above mentioned, there is a tendency that indicates a behavior that, when the red blood cells level is elevated, the voltage seen by the machine is low. On the contrary, if the concentration of red blood cells is low, a higher amount of light will be able to pass through the finger causing an increment on the voltage seen by the device.

Conclusions and future work

Conclusions

By using a non-invasive method allows online monitoring, without patient pain, and without risk of infection. According to the results obtained in the sampling process, each of the measurements made in the patients present variation in nail thickness, and as a result, the amount of light that the photosensitive sensor receives will vary depending on it. In relation to the tests carried out on women, another important factor that interferes with the measuring is the presence of nail polish. During the sampling process, measurements in patients with colored nails had to be discarded to get a more accurate result.

This means that, due to the fixed structure of the receptacle that allows the device to take a given sample, patients with finger sizes differing of those established will experience variations in the measurement. In this sense, it is necessary to improve the design of the receptacle where the optic devices are located, to achieve a more versatile device, similar to a pulse oximeter probe.

According to the related works, when performing the red blood cell count through image processing, good results are obtained with an average accuracy of 91–94% in relation to the results obtained in laboratory tests or manual counts of Red blood cells. Nevertheless, despite being a non-invasive method, it is necessary to perform data processing and use specialized hardware to obtain the measurements. On the contrary, when using the proposed device, it is possible to obtain the data in real time and with an average accuracy of 99.6%. Therefore, this device is viable because more accurate measurements are obtained, in a faster way and above all because it is a low-cost device.

Future work

It would be interesting to implement this measurement process through a mobile application to monitor patients, that is, to act as an alert to direct relatives, or that doctors can access the history remotely.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Research involving human participants Patient measurements were collected in accordance with the code of conduct of research with human material in the Mexico. The sampling process was made at the Dr. Martiniano Carvajal Hospital facilities in Sinaloa, Mexico. All subjects gave written informed consent.

Informed consent Informed consent was obtained from all individual participants included in the study.

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