BWard: An Optical Approach for Reliable in-situ Early Blood Leakage Detection at Catheter Extraction Points*

Juan P. F. Cortés, Tsz Him Ching, Chuyi Wu, Chang Yin Chionh, Suranga Nanayakkara, and Shaohui Foong†, *Member, IEEE*

***Abstract*—In the first few hours following the removal of central venous catheters, severe bleeding from the wound site may occur. These wound sites are pre-emptively heavily bandaged up and placed under blankets. Despite close and regular inspections, catastrophic bleeding may occur and remain undetected, possibly resulting in fatality. Hence, this paper presents *BWard*, an effective stand-alone electronic platform devised to monitor the extraction point of catheters for critical re-bleeding, and to alert medical staff immediately should bleeding be detected. This sensor employs two techniques – The first is a sensor fusion technique that exploits the unique light absorption spectra of the hemoglobin to differentiate blood from other bodily fluids. The second is a moisture sensitive electric circuit that is able to detect the presence of liquids in the dressings. A preliminary experimental evaluation of the BWard prototype done with blood of various concentrations showed a 100% detection accuracy. This demonstrates the potential of this technique.**

Keywords—sensors, blood detection, light absorption, Central Venous Catheters

I. Introduction

The risks associated with the use of venous lines and catheters are of great concern to the medical community. Central Venous Catheters (CVC) refers to prolonged vascular access devices indicated for the administration of intravenous medication treatments, fluids, stem cell infusions, parenteral nutrition and hemodialysis among others [1]. Main blood vessels such as subclavian, jugular or femoral veins are often the favored choice for this procedure. Complications during the catheter insertion, the catheter indwell period, and the catheter removal have been widely reported and include bloodstream infections, CVC dysfunction over time, thrombosis, major bleeding and embolism [2].

In general, hemorrhages involve unacceptable exposure, not only because the blood loss significantly aggravates the patient's medical condition, but also because the stabilization and replacement of any undergoing treatment carries a high price. Unfortunately, in 1% of the cases, external and intense hemorrhages have been reported during the first few hours after the successful extraction of CVC. If this happens, urgent detection is crucial, and a proper control of the bleeding is mandatory. Although the protocols and policies to prevent this scenario greatly differ among the centers [1], active medical supervision is always required in order to restrain the hemorrhage. To this end, it is required that a specialist assess the site for signs of bleeding Q15 min x 8 and Q30 min x 4 after the extraction of CVC. Hence, not only does this protocol require routine inspection from medical personnel, but also leaves the wound unsupervised for a considerable periods of time between checks.

There is little research conducted on active bleeding detection following the removal of the CVC, but some related studies do focus on hemorrhages induced by venous needle dislodgement. Part of these technologies makes use of light-based sensors, which are widely used due to their versatility and availability on the market. Redsense [3] presents a medical device capable of detecting venous needle dislodgement through a sensor probe that is based on optical fiber technology. A light pulse is sent through the fiber and, in presence of blood, the intensity of the returning light pulse will be reduced. Other solutions such as [4] are capable of detecting needle dislodgement by using an attached photo sensor. The sensor is placed under an opaque cover so that it would not be exposed to the ambient light while the needle remains in place. Moisture detection systems have also been extensively explored due to their low cost and simplicity. Work such as [5] uses a sensor pad with a unique electrical pattern overlying the vascular access region to monitor for blood presence. Other techniques include devices that are capable of measuring heart rate or detecting breaks in the electrical circuit composed by the dialysis machine, the patient and the needle. Unfortunately none of them has been found to provide a sufficiently reliable and cost effective solution to the problem [6].

Therefore, the aim of this research is to develop an effective real-time monitoring system, *BWard* that is capable of detecting intense external bleeding following the removal of the CVC. This system should also alert medical personnel in the event whereby their intervention is necessary. In the next few sections, the concept and theoretical background of *BWard* will be introduced i.e. analysis of the system; fluid detection principle; prototype implementation details; and experiment results. Contributions of this paper can be summarized as such,

- Introduction of a novel hemorrhage detection method that exploits the light-fluid interaction properties and the electric conductivity characteristics of the liquids.

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J. P. F Cortés, T. H. Ching, C. Wu, S. Nanayakkara and S. Foong are with the Engineering Product Development Pillar, Singapore University of Technology and Design, Singapore, 8 Somapah Road, Singapore 487372.

C. Y. Chionh is with the Division of Renal Medicine, Changi General Hospital, 2 Simei Street 3, Singapore 529889.

† Corresponding author: foongshaohui@sutd.edu.sg

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- Development and performance of a cost and power efficient stand-alone prototype shall be extensively evaluated.

II. Theoretical Background

The use of light as a sensory detection tool is a widely researched topic in many fields including biomedical, security, astrophysics and forensics. Since the discovery of X-Ray in 1895, emissions across the whole electromagnetic spectrum has been effectively used in the biomedical industry for medical imaging and diagnosis. For example, Nuclear Medicine operates using gamma rays (< 0.01 nm), X-Ray applies Hard X-Rays ([0.01 , 0.2] nm), Capsule Endoscopy uses visible spectrum ([390, 700] nm), Oximetry takes advantage of Near Infrared ([0.75 , 1.4] µm), Thermography benefits from Long-wavelength infrared ([8, 15] µm), some techniques for breast Cancer detection are based on Microwave Wavelengths (> 1cm) and even MRI makes use of Radio-Waves (> 4.7m).

Motivated by these, we envisioned a light-based approach to detect intense bleeding after the removal of CVC. The identification of blood depends on meeting two conditions: 1) detection of fluids i.e. water, urine and blood; 2) differentiation of blood from other substances via its light absorption characteristics.

A. *Light absorption Characteristics*

Since every known substance shows a specific spectral response, the detection method proposed for *BWard* will be based on the light absorption properties of hemoglobin, a biomolecule found in red blood cells. Hemoglobin is responsible for carrying oxygen in the bloodstream. Thus, the challenge is to use the optimal light wavelengths that will clearly differentiate hemoglobin from other substances that may lead to a false positive. With the right wavelength, the blood would show high levels of absorption while the other substances would not, or vice versa. As shown in Figure 1, hemoglobin has a maximum light absorption window between 520 and 580 nm. On the contrary, both water and urine offer very low absorption levels at these light wavelengths, creating a high contrast with hemoglobin. Although other high contrast windows for blood detection can be found in the ultraviolet and infrared range, few cost effective sensors and emitters that operate in these regions exist. Therefore, taking everything into consideration, the wavelength chosen to differentiate hemoglobin was 528 nm.

However, mere detection of hemoglobin is not the complete solution for *BWard*. Very diluted blood and other fluids need to be successfully detected as well (E.g. when a change of dressing is needed). To this end, an optimal wavelength that would allow detection of aqueous solutions was sought. The energy band where water shows high light absorption is far in the Infrared region. However, due to the scarce existence of sensors and their high economic cost, light at 950 nm was chosen instead (Figure 1).

In summary two different wavelengths are being used in this project, one at 528nm to specifically differentiate hemoglobin and the other at 950nm to expose the presence of fluids.

B. *Resistive Based Moisture Electric Detector*

In addition to the light approach mechanism, a parallel method to reveal fluid presence was explored. This approach is based in an electric resistive pattern sensitive to the presence of conductive liquids. The sensor consist of two electrodes, one sends an electric pulse while the other is passive. In presence of ionic liquids, the resistance of the medium decreases, thus allowing the flow of electricity towards the other electrode. If the current through the second electrode is big enough, the presence of a conducting substance will be evidenced. Blood has an average electrical conductivity of [0.61, 0.70] S/m, urine conductivity oscillates between [0.11, 0.39] S/m and drinkable water conductivity ranges from [0.0005, 0.05] S/m [13][14]. Therefore, a simple threshold mechanism will be enough to manifest the presence of water. If this requirement is met it implies that *BWard* will effectively detect blood, serum or urine. Choosing the pattern was an empirical procedure- several designs were printed and the most sensitive one was chosen.

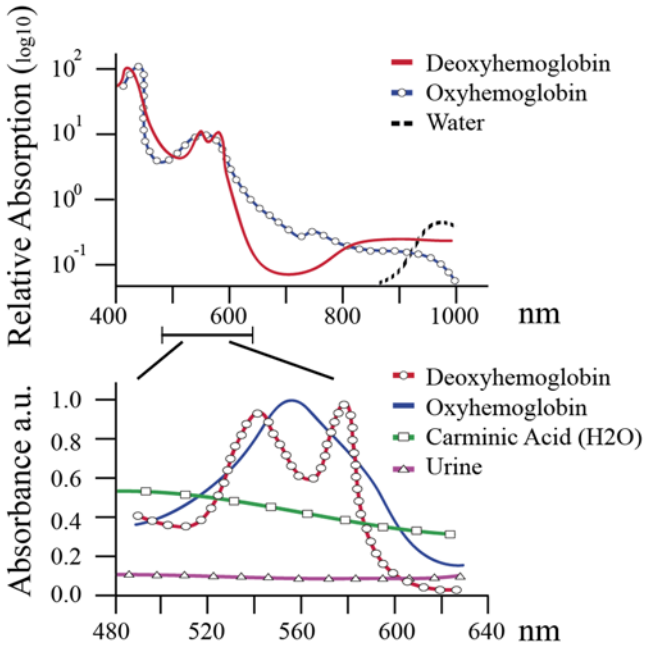

Figure 1.Absorption spectra comparison [6][7][8][9][10][11][12]

III. IMPLEMENTATION

Two objectives shall be attained by this project, one is the reliable blood detection and fluid differentiation while the other is the implementation of an effective alarm system. The first objective was achieved by devising *BWard*, a stand-alone device that integrates the sensing capabilities and the processing power required to monitor the dressing for fluid presence. The second objective was addressed by endowing *BWard* with an inbuilt alarm and with a Low Energy Bluetooth (BLE) module to trigger a remote warning system. In order to manage the *BWard* wireless communications, a separate device, *BHarbor*, was conceived (Figure 2b). Although *BHarbor* is still under development and thus only *BWard* was considered in the study, it is mentioned in this section to help with the overall understanding of how the system works.

Figure 2. a) *BWard* prototype placed over a clean dressing b) System overview.

Thus, *BWard* will be installed over the bandage on top of the extraction point after the removal of the catheter and will continuously monitor the dressing for active bleeding. In an event of hemorrhage or fluid presence, BWard will trigger its own alarm while simultaneously sending a signal to *BHarbor*. Finally, once the signal is received, *BHarbor* will activate a much louder alarm at the nurse station and notify, if applicable, the alerting devices that nurses and doctors in some hospitals carry on them.

A. BWard prototype

This first prototype (Figure 2a) will reveal the presence of fluids using two separate modules, the first is the resistive moisture detector (Figure 3b) and the second is the infrared emitter-photodiode centered at 950nm. Once liquid presence has been detected, *BWard* will make use of light at 528nm to determine if this liquid is blood. Furthermore, because *BWard* is intended to work in presence of liquids without external light interferences, a thorough casing design was developed. This casing (Figure 3c) isolates both the electronics and the sensors. The cover consists of 2 parts. The external cover, which will be exposed to body fluids, acts as a shield and incorporates the printed circuit board (PCB) with the resistive moisture detector. The second piece contains the core that includes the system circuitry (Figure 3a).

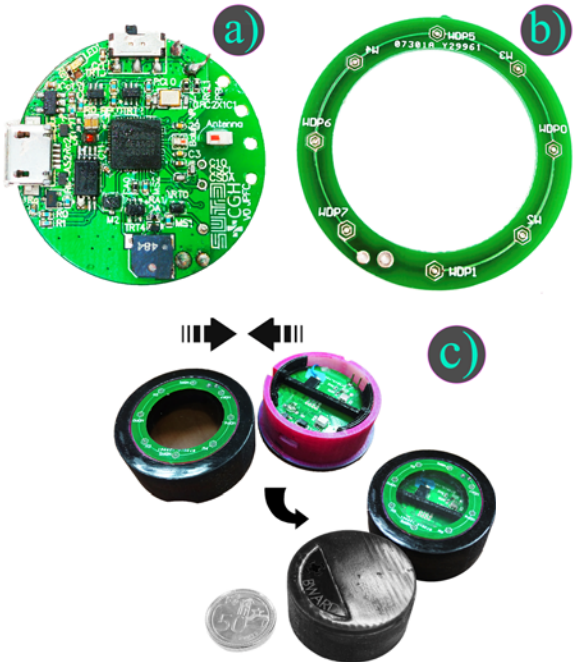

Figure 3. a) *BWard* core PCB circuit b) PCB Electric moisture pattern detector c) Casing parts.

The *Bward* prototype has a diameter of 4cm, height of 1.7 cm, and overall weight, including the casing, of 52.4gs The average power consumption is approximately 60 mAh since optimizing the energy consumption of the device was not the priority of this study. The wireless capabilities were effectively tested indoors at a maximum distance of 20m.

As shown in Figure 4a and Figure 4b, sensors, emitters and peripherals are driven using an MCU-BLE Transceiver (NRF51822). This chip embeds a low energy consumption Cortex-M0 (16 MHz, 3.3V, 32 bits) microprocessor and a BLE module. For the humidity sensing, an IR-emitter (TSML1020) with 30º beam angle centered at 950nm was selected in combination with a high speed, high sensitivity photodiode (VBP104FAS) with 130º viewing angle and the maximum spectral response at 950nm. Finally the photodiode input is driven into a current to voltage converting amplifier (TL082). As for the hemoglobin detector, a high luminosity and high viewing angle RGB LED (LRTBGFTG T7AW) centered at 470nm, 528nm and 625nm was chosen in combination with a high speed color sensor (TCS3414FN) centered at 470nm, 524 nm and 640nm. Finally, a 75dB magnetic buzzer (CSS 0575A) was found to be the best option for the alarm system.

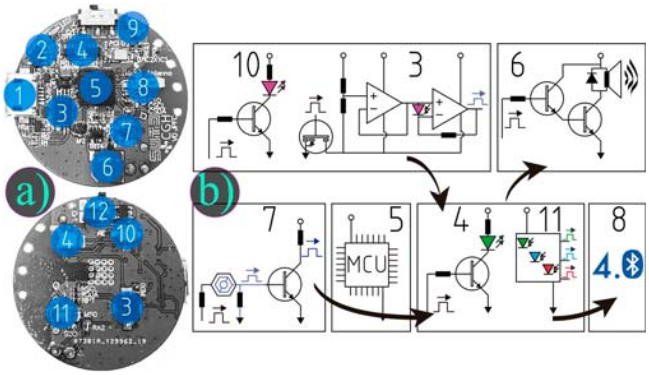

Figure 4. a) PCB top view and bottom view incorporating *BWard* modules labels: 1-Charger and programmer, 2-Battery Control, 3-Receiver 950nm, 4-Emitter 528nm, 5-MCU, 6-Alarm, 7-Resistive humidity detector, 8-BLE, 9-Battery, 10-Emitter 950nm, 11-Color sensor, 12-Voltage regulator. b) System flow diagram

Upon activation, *BWard* is placed between the dressing and the compressive bandage that holds the medical gauze in place. As shown in Figure 4b the light-based system detection at 528nm will only be activated when either the resistive electric pattern placed in the disposable element or the infrared module at 950nm acknowledges the presence of fluid. Once the presence of fluid is determined, the transmission of pulses at 528 nm begins. As long as the fluid is not blood, or if the blood concentration is small, the light will be effectively reflected from the surface of the bandage and therefore the sensor will receive a significant amount of luminous intensity. However, if the fluid is blood and the concentration is high enough, the light will start to be absorbed by the hemoglobin to a point where the sensor will cease to receive sufficient light (Figure 5). Once this occurs the inbuilt alarm will be activated and the warning signal will be sent to *BHarbor* via Low Energy Bluetooth (Figure 4b).

Figure 5. *BWard* measuring the amount of light at 528nm reflected in presence of different blood concentrations.

IV. PERFORMANCE EVALUATION

The main objective of the experiment is to assess the effectiveness of the *BWard* device in the presence of artificial blood. The artificial blood that is used in this study is an aqueous solution of Carminic acid. Although it is not Hemoglobin, it shows similar levels of absorbance at the wavelengths of interest [8][9][11]. Therefore, if the system evaluation is successful, it would indicate that in a future study, *BWard* could be potentially used to detect and differentiate real blood.

Four experiments were conducted in this study. The first aims to test the effectiveness of the resistive moisture detector. The second evaluates the performance of the light at 528 nm in differentiating fluids. The third analyses the capabilities of the light at 950 nm as a liquid detector and, in the fourth, the behavior of the entire system in presence of real blood is observed.

The first three experiments were tested in a very systematic way. In each experiment, gauzes of 7x7 cm were organized in columns of six rows. Depending on the number of dimensions of the experiment more columns were added (E.g. Rows represent the volume of a certain fluid while each column represent a different fluid). A total of 300 samples were taken per column (i.e. Fifty sets, each consisting of six readings, one for each row).

A. Experiment one: Moisture electric detector pattern effectiveness

The purpose of this experiment is to prove whether the resistive electric circuit can be activated on presence of fluid. That being so, if the sensor is sensitive enough to detect water, it is presumably safe to infer that the presence of the other bodily fluids with a higher conductivity will effectively trigger the sensor response.

Design and Method. To evaluate the humidity sensitivity, dressings soaked with different volumes of water were tested. Six gauzes of 7x7 cm, each one of them with a different liquid volume, were placed over a non-absorbent acrylic surface and after 1 minute, giving time for the bandage to absorb the fluid, the respective three hundred samples were collected. . Before each reading, the excess of humidity on the sensor was removed and then it was randomly positioned over the next dressing.

Results and Discussion. A one way ANOVA with a Bonferroni correction and a confidence level of 99% was used to analyze the statistical significance of each interaction. The findings (Figure 6) shows a mean effect for water volumes. Post-hoc analysis shows that the sensor can be triggered by any of the liquid volumes under test with a minimum mean difference of 28.56 (SE = 2.794, $p < 0.01$). Thus the sensor can be configured to be triggered at higher or lower levels of humidity (in *BWard* the threshold level was set to 200).

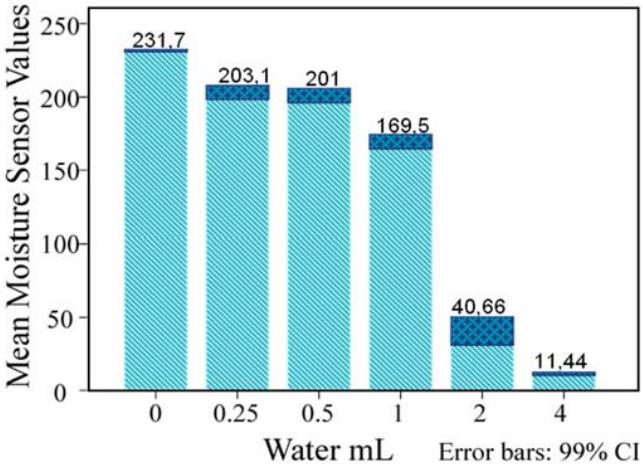

Figure 6. Mean electric moisture sensor values as a function of water volume

B. Experiment two: BWard effectiveness at 528 nm

In the second experiment, the effectiveness of 528nm light as a distinctive artificial blood-serum differentiator was investigated. The first validation factor for *BWard* is to be sensitive enough to reveal very small amounts of blood, even though in real scenarios the bleeding is generally abundant. The second factor focuses on a common condition, i.e. when the blood is diluted and the hemoglobin and hematocrit levels are low.

Design and Method. For the experiment, eighteen gauzes of 7x7 cm were positioned over a non-absorbent acrylic surface in a matrix of 6x3. Under the acrylic, dry and sterile gauzes were placed to avoid undesired absorptions or reflections from the surface of the table. Each row represents a different concentration of artificial blood, 0.01 mL was diluted according to the following ratios [artificial blood: serum]: [0:1] [1:20], [1:10], [1.7], [1:4] and [1:0]. Each column contains a different volume of the solution, 0.005 mL, 0.01mL and 0.03mL respectively. Next, a total of nine hundred samples was acquired. Although it was intended that *BWard* be positioned directly over the bloodstain prior to each measurement, the inability to do so with precision added a confounding factor that increased the variety of the samples.

Results and Discussion. A two way ANOVA with a Bonferroni correction and a confidence level set to 99% was used to analyze the statistical significance of each interaction. The results (Figure 7) are statistically significant across all conditions and reveal that even with the smallest tested amount of volume and blood concentration the fluid differentiation is still highly substantial. So, for instance, at 0.05mL volume the minimum mean difference between 0% blood concentration and 5% is 31.820 (SE = 1.358, $p < 0.01$). Thus it can be said that the sensor is sensitive both to the volume and concentration levels. Even in the most critical case whereby concentration is low, *BWard* will trigger a response given a substantial amount of artificial blood.

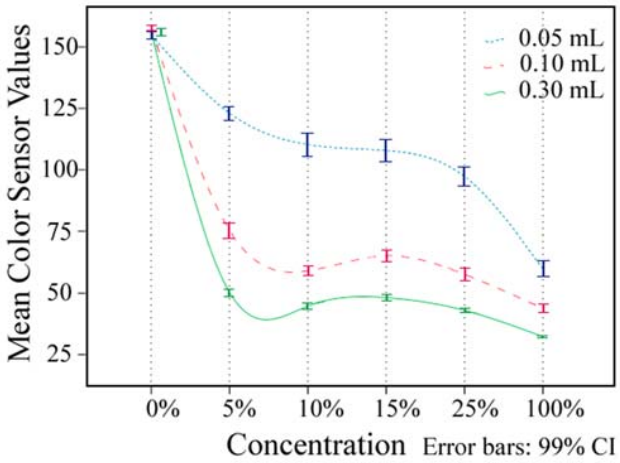

Figure 7. Mean color sensor values at 528 nm depending on artificial blood volume and concentration

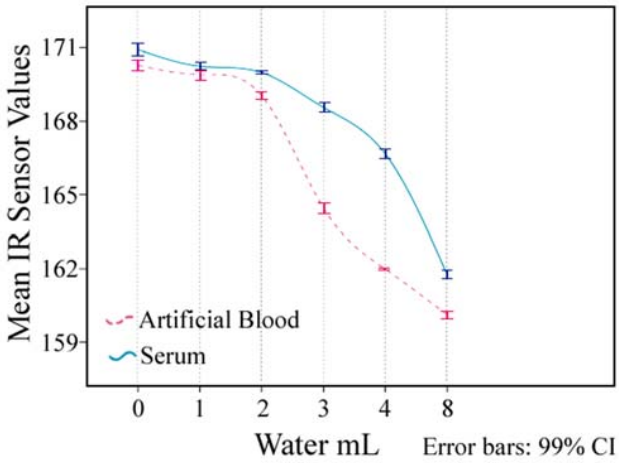

Figure 8. Mean color sensor values at 950 nm depending on type of fluid and volume

C. *Experiment three: BWard effectiveness at 950 nm*

The conducted experiment analyzes the effectiveness of the 950nm wavelength to reveal the presence of fluids on the dressing. Hemoglobin, urine and Carminic acid show light absorbance at this frequency. Assuming that these substances are always dissolved in aqueous solutions, the test will be performed using serum, which is nothing more than salt water.

Design and Method. For testing the hypothesis, twelve gauzes of 7x7 cm were positioned over a non-absorbent transparent acrylic sheet in a matrix of 6x2. Under the acrylic, dry and sterile gauzes were placed to avoid undesired absorptions or reflections from the surface of the table. Each row represents a different volume of liquid. Each column contains a different substance. One contains serum and the other contains non-diluted artificial blood. A total of six hundred samples were collected.. Between readings, *BWard* was cleaned, removed and then randomly positioned over the next dressing.

Results and Discussion. A two way ANOVA with a Bonferroni correction and a confidence level of 99% was used to analyze the statistical significance of each interaction. The results (Figure 8) are statistically significant and indicate that this moisture detection method is only reliable when the dressing is highly sodden. Hence, a confidence threshold could be set at 3mL volume level at which the mean difference between the dry dressing is 4,090 (SE = 0.07, $p <$ 0.01). The results also suggest that luminous intensity decreases more in presence of absorbent substances such as Carminic acid. This demonstrates the infrared response may be triggered at much lower volume concentrations, and allows for a better contrast if the fluid is different from water.

D. *Experiment four: BWard effectiveness in presence of real blood*

To test the performance of *BWard*, a preliminary evaluation was conducted using three real blood samples from different hemodialysis patients (Figure 9). Due to the short shelf-life of the samples, only one set of readings could be acquired for each patient.

Design and Method. The independent variable was the blood dilution i.e. 100%, 50% and 25%. The first dependent variable was the volume (in milliliters) needed to trigger the alarm of *BWard*, the second was to evaluate whether or not the detection was successful.

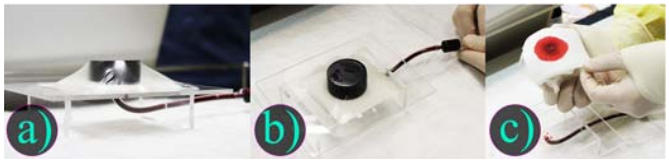

Figure 9. a) *BWard* testing real blood set up b) Real blood being injected in the dressing c) Dressing after detection positive blood detection

Results and Discussion. The results displayed in Table 1 illustrates the effectiveness of *BWard* in detecting blood across all conditions, specifically in the most critical scenarios with low hematocrit recount and low concentrations of hemoglobin. Due to the small sample size, further studies will be carried out to verify the generalizability of the detected trends.

Table 1. Real Blood Testing Results

Hematocrit	Hemoglobin	Blood Conc. [Blood:Serum]		
Typ. [36, 46]%	Typ. [11.5, 15] g/dL	1:4	1:2	1:0
23.6	8	Detected at 0.7 mL	Detected at 0.9 mL	Detected at 0.4 mL
19.5	7	Detected at 1.1 mL	Detected at 1.0 mL	Detected at 0.9 mL
37.9	12.7	Detected at 0.7 mL	Detected at 0.8 mL	Detected at 0.5 mL

V. CONCLUSION

BWard is envisioned to be a stand-alone device that effectively monitors the extraction point of Central Venous Catheters for external bleeding. To address this problem a hybrid solution was proposed and implemented. The first part to this solution is based on the light absorption properties of the substances. A mechanism to reveal and differentiate blood from other body fluids was devised. For the second part to the solution, a moisture detection mechanism that takes advantage of the electrical conductive properties of the liquids was developed.. The overall system was prototyped and an exhaustive examination was performed with different volumes and concentrations of artificial blood. To further validate the proposed claims, a first evaluation with real blood was conducted in presence of a medical practitioner. *BWard* demonstrated high levels of effectiveness in this preliminary evaluation. Therefore, great promise in the development of *BWard was seen*, and further studies to verify the generalizability of the detected trends are intended to be conducted.

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