Development of a diagnostic dehydration screening sensor based on infrared spectrometry

Cobus Visser, Cornie Scheffer, *Member, IEEE,* Kiran Dellimore, *Member IEEE,* Eduard Kieser*, and Johan Smith*

***Abstract*— The clinical assessment of dehydration is highly subjective and requires experienced and highly trained clinical personnel. At present no objective method for quantitatively determining an individual's dehydration status exists. The aim of this study is to address this deficiency by presenting the development and testing of a novel diagnostic tool for dehydration detection based on infrared spectrometry. Laboratory testing and two clinical studies were conducted to evaluate the efficacy of the device in both adults and infants. The results were promising for the infant study with a clear trend exhibited. However, a number of challenges must be overcome before this sensor can be applied in a clinical setting.**

I. Introduction

Dehydration is a common symptom of acute diarrhea which is characterized by an excessive loss of body water, accompanied by a disruption of metabolic processes. While dehydration affects individuals from all age groups, it is a particularly life threatening condition in infants since their turnover of fluids and solutes can be as much as 3 times that of adults due to higher metabolic rates, an increased surface area to volume ratio and higher total body water content [1]. Without appropriate intervention dehydration can cause shock due to loss of blood volume (i.e., hypovolemia), organ failure and even death [2-3]. Current clinical protocols for diagnosing the level of dehydration in infants include examination and scoring of various markers and vital signs. These include abnormal breathing pattern, capillary refill, eye appearance, fontanelle appearance, heart rate, level of physical activity, mouth dryness, mucus membrane appearance, pulse quality, skin turgor, as well as urine color and smell, and weight loss [4-5]. However, this approach is limited in its effectiveness by clinician subjectivity, skill and experience. Moreover, in rural and resource limited settings, clinicians may not always follow conventional clinical practices due to a lack of appropriate training, high patient loads or inadequate facilities [6-7].

Early detection of dehydration and intervention in infants is important since nearly all fatalities attributed to dehydration caused by diarrheal diseases can be prevented through the use of an inexpensive solution of glucose and sodium (i.e., oral rehydration salts) [8]. It is therefore imperative that a more objective and quantitative means of determining infant dehydration is developed.

Over the past 30 years there have been several attempts to develop markers for the assessment of dehydration including ingestion and analysis of isotope solution, bioimpedance analysis, urine analysis, plasma analysis, and loss of body mass [9-10]. All of these markers have to date failed to adequately objectify and quantify dehydration. However, infrared spectrometry may be a promising method for diagnosing dehydration, as it has already been used to investigate skin hydration [11]. Moreover, previous work by Nachabé et al. [12] investigated the estimation of water and lipid concentrations in a scattering medium. By investigating the spectrum ranging from near-infrared to short-wavelength infrared (900-1600nm) Nachabé was able to estimate the concentration of water and lipid phantoms with less than 5% error, due to the prominent absorption coefficient peaks in this region. Nachabé et al. acknowledges that it is possible to measure, in real time, the lipid and water content in tissue through the use of infrared spectrometry.

The aim of this study is to present the development of a novel diagnostic tool for the objective assessment of dehydration in infants based on infrared spectrometry.

II. Methods

A. Dehydration sensor design and implementation

The main design requirements for the diagnostic dehydration sensor are that it should be: 1) non-invasive, 2) easy to use, 3) quantitative, and 4) low cost.

To meet these requirements a prototype infrared dehydration sensor (IDS) was developed using two infrared LEDs (LED1300-series and ELD-1480-525, Roithner LaserTechnik, Austria) which produce light at 1300 nm and 1480 nm, respectively (Fig. 1). These two wavelengths were selected to ensure that they possessed water absorption coefficients which have a large difference in magnitude. The smaller magnitude absorption coefficient at 1300 nm was chosen in order to maximize the depth of penetration into the skin, while the larger magnitude absorption coefficient at 1480 nm was chosen because of its sensitivity to water at various concentrations. The LEDs were used in conjunction with an IPD14-12-5T photodiode (Roithner LaserTechnik, Austria) that measures the part of the far infrared spectrum between 1000 nm and 1600 nm. The LEDs and photodiode were mounted so that the sensing area of the photodiode and the light inducing area of the LEDs lie in the same plane (Fig. 2). This is to ensure that when pressed onto the skin all

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978-1-4244-9270-1/15/$31.00 ©2015 IEEE

Fig. 1. (top) Photograph of the IDS (bottom) the IDS in use.

background light will be cut off from the photodiode and the only light measured will be due to the two infrared LEDs. A current to voltage amplifier (TS9121D, STMicroelectronics, USA) was also included to amplify the sensing current to a measureable threshold. The device attaches to a portable microcontroller (Arduino UNO32, Digilent Inc., USA) and a power supply hub. The analog signal from the device is converted to digital format via the microcontroller's 10-bit ADC, and then sent to a PC via Wi-Fi (Fig. 3). Data can be acquired and transmitted every 0.5 seconds with values recorded only after steady state has been reached. To ensure the device is suitable for use on infants the circuitry was encapsulated in silicone rubber (Mold Max 30, Smooth-on, USA). The silicon housing ensured that the device was biocompatible, electronically isolated from the skin and that all sharp edges were smoothed.

B. Testing Procedure

The performance of the IDS was evaluated by conducting a modified sorption-desorption test in the laboratory, as well as by performing in vivo clinical studies on adults and infants. The standardized sorption-desorption test involved measuring the stratum corneum before and after the application of a water droplet with measurement taken every 30 seconds over a period of 5 minutes [13]. To eliminate potential interference caused by the water droplet a modified version of the sorption-desorption test was applied to ensure

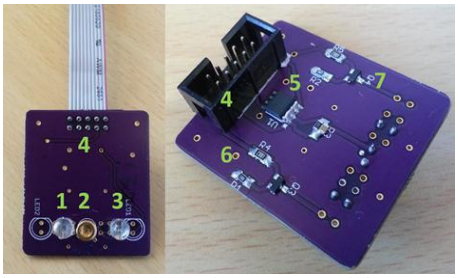
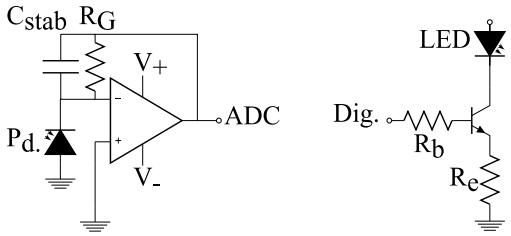


Fig. 2. Photograph of the internal components of the IDS: 1. 1480nm LED, 2. Photo-diode, 3. 1300nm LED, 4.Ribbon Connection, 5. Current to voltage amplifier, 6 and 7. Transistors switches for LEDs.



R_G	10MΩ	V±	±2.5V	LED	LED1300-series
R_b	3kΩ	C_{stab}	100nF	LED	ELD-1480-525
R_e	36Ω	Opamp	TS912ID	Pd.	IPD14-12-5T

Fig. 3. (top) Circuit diagram depicting the current amplifier and infrared LEDs (bottom) Schematic of the analog and digital interface.

that a larger area is hydrated to measure with the diagnostics device. This process involved wetting a piece of cloth with warm water and draping it over the forearm in such a way as to allow the water vapor to be absorbed by the skin surface (i.e., stratum corneum). Three tests were conducted to evaluate the performance of the device using the modified sorption-desorption approach: 1) No hydration (i.e., dry skin), 2) wetting for 1 minute and 3) wetting for 5 minutes. Each test was repeated seven times to ensure repeatability.

The adult and infant studies were approved by the Stellenbosch University Human Research Ethics Committee (#S13/10/204, "Quantitative Hydration Sensor Development Adult/Infant Testing"). Written consent was obtained from all of the adult participants and from the parents of the infants, prior to enrolment in the study.

A total of 9 subjects were recruited for the adult study including 5 males and 4 females (age = 23.4±1.59 years, BMI = 24.9±3.3). The adult tests were performed over a period of 6 days, with all exercise sessions conducted at the Stellenbosch University Sport Performance Institute under the instruction of a sports trainer. The first phase of the test involved establishing the subjects' euhydrated state over a 3 day period. Subjects consumed prescribed amounts of water (1L between waking and 18:00 and 2L from 18:00 to 22:00 each day) with measurements taken each morning at the same time. From the fourth to the sixth day, the second phase of the test was conducted with the participants completing three, 50 minute long, strenuous exercise sessions each day to induce body weight loss. Each exercise session was followed by a 10-20 minute rest period, after which physiological measurements were taken by a registered nurse and data were acquired using the IDS. For consistency, all measurements were taken from the ventral side of the right forearm of each subject while for safety reasons exercise was stopped if the measured weight loss was more than 4% (i.e., mild hypertonic hypovolemia). Subjects had a choice between several cardio exercises including cycling, rowing, jogging or using an elliptical machine. The exercise intensity was measured through the on-board display of the exercise machines, with a target exercise intensity of 120 W. In the cases in which no on-board measurement of exercise intensity was available qualitative assessment of the subject

was performed by observing the subject's respiratory effort, perspiration and fatigue level.

The infant study was conducted at the Paediatric Ambulatory Admission Unit of the Tygerberg Children's Hospital. A total of 4 infants were recruited for the study (ages 3-36 months, weight = 7.3±1.04 kg). All of the infants enrolled in the study had succumbed to gastrointestinal distress leading to isotonic hypovolemia. All infants received standard care involving the administration of oral rehydration salts. Measurements were taken during the rehydration therapy period using the IDS on the stomach of the infant when the nurses performed their daily rounds. The dehydration level was also scored by experienced doctors using the Gorelick scale [14].

C. *Data Analysis*

The data analysis and processing was performed offline using the mathematical software MATLAB® (Mathworks Inc., USA). In the adult study statistical significance was calculated through linear regression, using the IDS results and the percentage weight loss as the dependent variable. The measured data were also compared to other measured parameters, including environmental factors (temperature, humidity etc.) and physiological factors (heart rate, blood pressure etc.). In the infant study due to the small patient population enrolled only qualitative assessments were made with regards to the comparison of the measurements and the results expected based on theory. In both the adult and infant studies, measured weight loss was used as a 'gold standard' reference marker for dehydration. In the adult study all weight changes during the exercise period were assumed to be only due to water loss. Changes in lipid and hemoglobin concentration, the other dominant absorbers of infrared light in tissue, were assumed to be negligible over the short duration of the study. In the infant study the weight at hospital discharge was assumed to be the euhydrated weight.

III. RESULTS

Fig. 4 shows the measured results for the modified sorption-desorption tests. In both cases the measured intensity

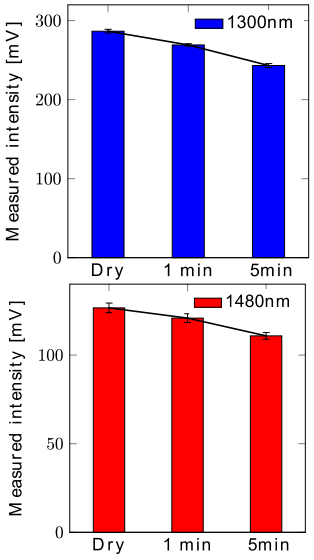


Fig. 4. Modified sorption-desorption test results using the IDS at 1300 nm (top) and 1480 nm (bottom).

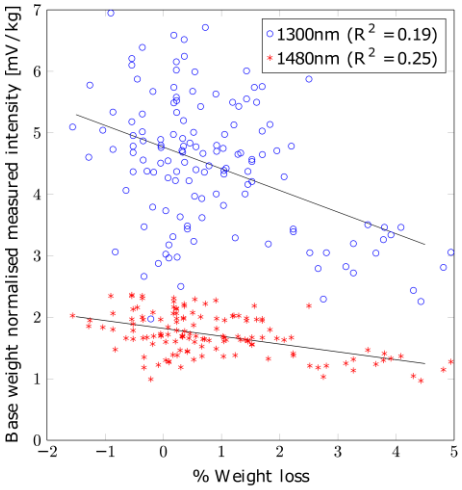


Fig. 5. Grouped results from the adult study for 1300nm ('o', y=-0.35x+4.8) and 1480nm ('*', y=-0.13x+1.8).

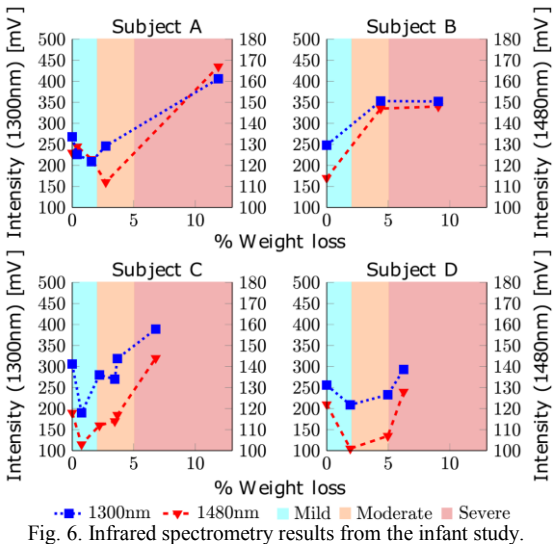


Fig. 6. Infrared spectrometry results from the infant study.

for different levels of hydration declined with the onset of higher levels of hydration. The decrease in intensity from dry skin to skin wetted for 1 minute and 5 minutes was 6.0% and 9.7% at 1300 nm, respectively. At 1480 nm the decrease in intensity was less pronounced with a drop of 4.6% and 8.3% observed from dry skin to skin wetted for 1 minute and 5 minutes, respectively. In all cases the magnitude of the measured intensity was on average 55% less for the 1480 nm light than the 1300 nm light.

Fig. 5 shows the grouped IR measurements from the nine subjects of the adult study. The 'o' and '*' symbols correspond to the measurements at 1300 nm and 1480 nm. The data presented do not show high levels of correlation at either wavelength. The measurements at 1480 nm had a lower intensity and were less scattered than those at 1300 nm. In general the measured wavelengths yielded a negative trend.

Fig. 6 presents the measured IR results of the four infants. The '■' and '▼' symbols correspond to the measurements at 1300 nm and 1480 nm, respectively. The figure shows that, in general, below 2% weight loss the measured intensity increases and from approximately 2% weight loss and upwards the measured intensity increases.

IV. DISCUSSION

The results presented in Fig. 4 indicate that the measured infrared light intensity decreases with increasing hydration of the stratum corneum. This is consistent with theoretical expectation since at higher chromophore concentrations more infrared light is absorbed resulting in a decrease in the measured absorption intensity, which was observed at both wavelengths. This result suggests that the IDS is capable of distinguishing between different levels of skin hydration.

The data shown in Fig. 5 for the adult study are inconsistent with expectation from theory since higher infrared absorption intensities should be observed at elevated dehydration levels due to the presence of fewer absorbing chromophores in the skin (which is a result of restricted blood flow caused by vasoconstriction due to the body's attempt to maintain homeostasis during dehydration). This result may be attributed to the accumulation of sweat on the skin from the rigorous exercise performed by the volunteers. This caused an increase in the water concentration leading to a rise in the number of infrared absorbing chromophores.

The infant data in Fig. 6 gives an indication that higher infrared absorption intensities are expected with the onset of mild to moderate dehydration. Noticeably the data show a generally increasing trend with the onset of dehydration from 2% weight loss and upwards. Below 2% weight loss an inverse trend is observed, with a higher intensity measured at the euhydrated state than at 2% weight loss for three of the four subjects (subjects A, C and D). For subject B, no measurements were taken between 4% weight loss and the euhydrated state, so no reliable inference can be made from these results. It is also important to note that at both wavelengths higher dehydration levels correspond to larger magnitude infrared absorption intensities in comparison to lower dehydration levels as observed earlier in the modified sorption-desorption tests (Fig. 4). The infrared absorption intensities in Fig. 6 show a decreasing trend with increasing body water from 10% weight loss up to 2% weight loss. This is consistent with expectation since increasing water concentration is associated with an increasing number of infrared absorbing chromophores, which will correspond to a decrease in the measured infrared absorption intensity. The observed behavior may be indicative of increased blood flow to the skin that was first restricted, due to vasoconstriction, when the subject was moderately to severely dehydrated, which in turn then slowly increases due to vasodilation, while the subject is rehydrating. The measurements taken in the range of 0% and 2% weight loss, however, are not consistent with expectation. This may be attributed to the altered morphology of the skin and blood cells. Friebel et al. [15] showed that the optical properties of blood can change due to various reasons, including blood flow, path length of blood cells, etc. It can be assumed that during rehydration, the blood cells may become saturated with water altering the path length and scattering behavior of the infrared light.

Although the infant study population was too small to allow statistically significant conclusions to be made, it is evident from the results that there are strong similarities between the data from the different subjects, with similar trends observed at both wavelengths.

V. CONCLUSION

This study presented the development and testing of a new diagnostic tool to objectively assess the dehydration status of an individual using infrared spectrometry. The performance of the diagnostic tool was evaluated by performing laboratory sorption-desorption tests and by conducting two in vivo clinical trials in adults and infants. The adult measurements were found to be inconclusive with measured intensity not found to be highly correlated with percent weight loss. The infant study in contrast yielded more promising results, with consistent trends observed in measured intensity as a function of weight loss. However, the population size enrolled is too small to make statistically significant conclusions. Future work, will explore using multiple wavelengths to enable a better estimation of dehydration status.

VI. ACKNOWLEDGMENT

The authors are grateful to Philips Research Asia and the THRIP Initiative for funding this research.

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