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Investigation of the feasibility of non-invasive optical sensors for the quantitative assessment of dehydration

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ABSTRACT

This study explores the feasibility of prospectively assessing infant dehydration using four non-invasive, optical sensors based on the quantitative and objective measurement of various clinical markers of dehydration. The sensors were investigated to objectively and unobtrusively assess the hydration state of an infant based on the quantification of capillary refill time (CRT), skin recoil time (SRT), skin temperature profile (STP) and skin tissue hydration by means of infrared spectrometry (ISP). To evaluate the performance of the sensors a clinical study was conducted on a cohort of 10 infants (aged 6–36 months) with acute gastroenteritis. High sensitivity and specificity were exhibited by the sensors, in particular the STP and SRT sensors, when combined into a fusion regression model (sensitivity: 0.90, specificity: 0.78). The SRT and STP sensors and the fusion model all outperformed the commonly used "gold standard" clinical dehydration scales including the Gorelick scale (sensitivity: 0.56, specificity: 0.56), CDS scale (sensitivity: 1.0, specificity: 0.2) and WHO scale (sensitivity: 0.13, specificity: 0.79). These results suggest that objective and quantitative assessment of infant dehydration may be possible using the sensors investigated. However, further evaluation of the sensors on a larger sample population is needed before deploying them in a clinical setting.

1. Introduction

Dehydration is a common consequence of acute diarrhea which is characterized by an excessive loss of body water, accompanied by a disruption of metabolic processes. While dehydration affects individuals of all ages, it is particularly life threatening in infants. This is because of their high turnover of fluids and solutes, which can be as much as three times that of adults due to their higher metabolic rates, increased surface area to volume ratio and higher total body water content [1]. Without appropriate intervention dehydration can cause hypovolemic shock due to loss of blood volume, organ failure and even death [2–3]. Dehydration resulting from acute diarrhea is among the leading causes of infant mortality globally, resulting in over 1.3 million infant deaths annually, with 99% of these occurring in developing countries [4].

The current "gold standards" for prospective dehydration assessment are hydration scales which aggregate various subjective clinical observations into a score used to gauge the level of dehydration of an infant [5–8]. Among the most commonly used clinical markers of dehydration include: breathing strength and rate, capillary refill, eye appearance, fontanelle appearance, heart rate, level of physical activity, mouth (mucus membrane) dryness, neurologic state, pulse quality, skin turgor, absence of tear production, thirst, temperature difference between core and extremities, as well as urine color and smell [5–10]. The three most widely utilized hydration scales, based on a subset of clinical dehydration markers, include the clinical dehydration scale (CDS), the World Health Organization (WHO) dehydration scale, and the 4-point or 10-point Gorelick hydration scale [6,7].

However, previous work has shown that these "gold standard" clinical hydration scales perform poorly when used in rural and resource constrained settings [6,8], where the overwhelming majority of infant deaths occur due to diarrheal diseases [4]. Among the main causes for this is the poor adherence to established clinical practice which can be attributed to a lack of appropriate training of clinical staff, high patient loads and inadequate facilities; and the high degree of subjectivity in the scoring of many of the clinical dehydration markers [8–9]. This motivates the need for a more objective and quantitative means of assessing infant dehydration, suitable for deployment in rural and resource constrained settings. Ideally this method should be non-invasive, easy-to-use (*i.e.*, require little training), reliable and low-cost.

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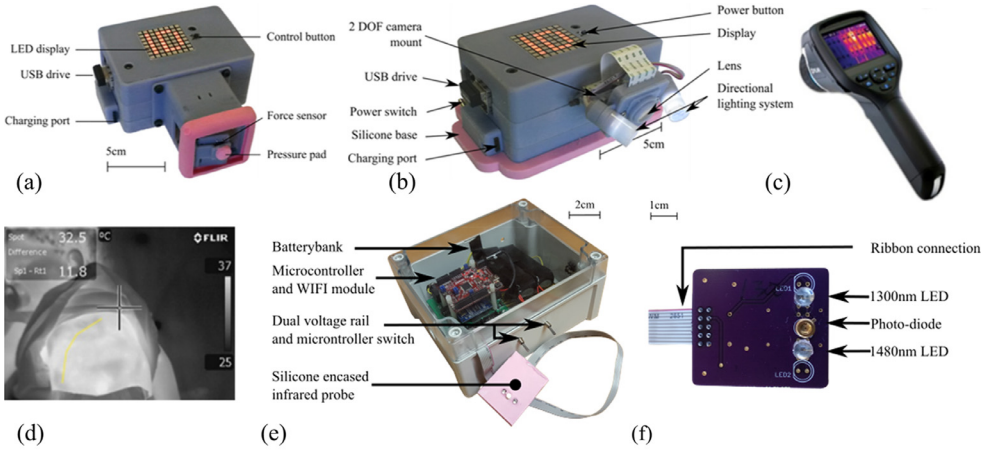

Fig. 1. Overview of the four hydration sensors developed to investigate: (a) CRT, (b) SRT, (c, d) skin temperature gradient and (e, f) infrared absorption as a surrogate measure of total water content.

Previous attempts at objectifying dehydration assessment using non-invasive techniques have focused largely on bioimpedance analysis (BIA), optical estimation of capillary refill time (CRT) and infrared spectrometry [11–25]. Koulmann et al. [11] investigated the estimation of the total water content using BIA in subjects who were dehydrated by exercise and heat stress, as well as glycerol induced hyper-hydration. They found that BIA could accurately estimate total body water in subjects who have succumbed to heat stress induced dehydration and glycerol induced hyper-hydration, but could only estimate total body water half of the time in subjects with exercise induced dehydration. Subsequently, Röthlingshöfer et al. [12] experimentally and numerically investigated the shift in impedance over varying frequencies in exercise induced dehydrated subjects. They showed that an impedance shift of 5–6% occurred as a result of exercise thereby suggesting bioimpedance as a potential marker for dehydration assessment. Both studies found that several confounding factors can influence BIA measurements leading to potentially unreliable prediction of an individual's hydration status. Utter et al. [13] found BIA to be sensitive in detecting a 3.5% reduction in body weight due to water loss in a study on the hydration status of collegiate wrestlers. However, they reported that BIA is a late dehydration indicator with respect to plasma and urinary markers.

CRT is a widely used dehydration marker since it is a fast and non-invasive method [14,15]. However, Blaxter et al. [15] and Pickard et al. [16] reported that manually performed CRT may be unreliable because it is influenced by many factors including age, ambient temperature, ambient light, pressure application and intra- and inter-observer reliability. Several studies have consequently attempted to quantify CRT objectively [17–21]. Shavit et al. [17] used digital videography to quantitatively measure the nail bed CRT of 83 children to assess the presence of severe dehydration ($>$ or $=$ 5% loss of body weight). They reported that digitally measured CRT yielded a specificity and sensitivity of 0.99 and 0.88, respectively, compared to manual CRT assessment which had a specificity and sensitivity of 0.85 and 0.60, respectively [17,20]. Subsequently, Bordoley et al. [18] and Kviesis-Kipge et al. [19,21] separately investigated optical CRT, but were unable to obtain consistent measurements. A possible drawback of these studies is that they determined CRT at the fingertip which may be a sub-optimal assessment site according to Strozik et al. [22,23] who found that CRT measurements at the sternum and forehead are more consistent than at the extremities.

Another non-invasive approach for objective dehydration assessment is near infrared (NIR) videography, which was studied by Attas et al. [24] to determine the hydration state of human skin. Although this work did not focus on the clinical assessment of dehydration, they were able to measure the distribution of moisture in the skin in the wavelength bands at 970 nm, 1200 nm and 1450 nm. Application of this approach to dehydration assessment in the skin is supported by Nachabé et al. [25] who investigated measuring the NIR spectrum of lipid and water phantoms and achieved measurement errors within 5%. They also concluded that NIR spectrometry may be useful for *in vivo* real-time measurement of dehydration in tissue.

This study aims to explore the basic feasibility of prospectively assessing infant dehydration using various non-invasive optical sensors based on the quantitative and objective measurement of several markers of dehydration: (i) skin turgor, (ii) capillary refill time, (iii) skin temperature gradient and (iv) infrared absorption as a surrogate measure of tissue water content. Sensor performance is evaluated by comparing sensor measurements with clinical assessments made during a clinical study on infants (aged 6–36 months) suffering from gastrointestinal distress.

2. Methods

2.1. Hydration sensors

Four different non-invasive hydration sensors were investigated to determine their ability to quantitatively assess dehydration severity:

1 *Capillary refill time (CRT) sensor* was designed to quantify the capillary refill test performed by clinicians. The sensor consists of a silicone pressure pad that is mounted on a swing arm, over a Honeywell FS1500 force sensor which is connected to a controller via an ADS115 16-bit analog to digital converter (ADC) as shown in Fig. 1(a). When the swing arm is locked into place it can be used to apply a blanching pressure for a prescribed time period (*e.g.*, 6 s) while the measured force output is shown on a 1.2 inch tri-color 8×8 LED matrix display to ensure that the applied force falls within a prescribed range (2.7–3.3 N). This range was determined by measuring the force applied by an experienced physician. After applying the force, the swing arm is withdrawn to allow the 5MP Raspberry-Pi camera (set to 1024×768 pixels at 30 fps) to start recording the refilling of the capillaries. Four white LEDs are used to ensure appropriate illumination, while power is provided by two, series connected, 3.7 V, 2000 mAh lithium polymer cells controlled by a LM7805 linear regulator. To enable the camera to focus on near-field