

Investigation to Detect the Hydration State with Continuous Monitoring of Vital Signs

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Abstract—A stable water balance is necessary for a functioning metabolism. Especially in daily routine dehydration is common. By data acquisition of different vital signs, which are influenced by changes in the total body water, a conclusion on the hydration status should be reached. The goal is to verify the equation for the determination of the total body water as well as the analysis of the hydration status by subsequent conclusion of the results. Seven participants are monitored during their daily routine. The parameters pulse, oxygen saturation, blood pressure, weight, skin moisture and skin conductance are detected. Based on the data acquisition, the total body water is calculated. Correlations between the vital signs and body weight can be detected. The results show that it's possible to measure the hydration status by detecting vital signs. However, a person-specific calibration is necessary. Further investigations must be carried out to analyze influencing factors.

Index Terms—hydration monitoring, dehydration, total body water, algorithm, vital signs

I. INTRODUCTION

A person loses up to 2.6 liters of water a day through perspiration, respiration and excretion [1]. Daily situations can lead to increased fluid loss. If this is not compensated for immediately by water intake, dehydration occurs. This condition is only manageable for the body to a certain extent and has physiological effects. Therefore, low levels of dehydration can lead to a feeling of thirst. If the degree of dehydration increases, it can lead to physical and mental performance reductions, but also to a circulatory collapse [1]. Dehydration is not a rare phenomenon, especially among older people. As older people increasingly no longer feel thirsty, they forget to drink fluids regularly [2]. In about 20% of the patients who are hospitalized because of dehydration die within 30 days [3]. Both in nursing homes and in home care, drinking protocols are kept daily to monitor fluid intake [4]. However, this method of determination is very time-consuming and cannot be performed continuously. In order to be able to measure the hydration status, a technology is currently being developed with which the Total Body Water (TBW) can be determined by means of continuous vital signs detection.

In this investigation it will be analyzed whether this technology can be used to determine the hydration status.

II. MATERIALS AND METHODS

An observational investigation will be organized for analysis. Regulation requirements have been taken into account and data protection has been preserved. The observation was on a voluntary basis and the consent of the participants to use the data for scientific purposes has been obtained. 7 participants are monitored exclusively during their daily routine in an office. The person monitoring covers two days. Since it is an observation of drinking behavior, termination criteria are defined at the beginning. One person had to be excluded because he did not go to the toilet during the observation despite a strong urge to urinate. Due to the fact that the degree of hydration was measured using a personal scale, no dehydration could be detected, although the fluid in the bladder is no longer directly available to the body for metabolic processes. If a person becomes too dehydrated or shows any of the symptoms listed in Table I, the observation is terminated and the measurement is discarded.

TABLE I. SYMPTOMS, WHICH LEADS TO A TERMINATION OF THE INVESTIGATION

| Termination criteria | Symptoms |
|----------------------|---|
| Body Weight | Decrease of > 5 % |
| Blood Pressure | Decrease of > 40 mmHg |
| others | Dizziness, nausea, headaches, severe thirst |

The health data of the participants are recorded for two days.

A. Procedure of the Observation

The first day was used for reference. On this day, the participants are constantly reminded to take regular amounts of fluids in order to detect the person's euhydrated state. The amount drunk is recorded in the drinking protocol. A simple and representative method of measuring total body water is the regular detection of body weight [5]. Therefore, every 30 minutes the weight of the participants is documented in a weight protocol.

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Additionally, toilet visits and lunch are noted. These additions and subtractions can be subsequently offset against the weight and guarantee an exact detection of the total body water.

The second day was used to determine the degree of dehydration. The participants are measured until they consume liquid. By continuously recording the body weight, the degree of dehydration can be determined afterwards. During the observation the vital signs of the participants are continuously detected. It is pointed out that only dry food is eaten on the observation day. In addition, on the second day of observation, a thirst protocol and a protocol for the participant's own well-being are filled out.

B. Technical Equipment

The data acquisition is implemented with 7 sensors. Selected sensors are attached to the participants to collect data continuously. Blood pressure and skin temperature are measured only 3 times a day. These parameters are mainly used to record the general condition. To detect the degree of dehydration, the weight is recorded using a body scale. Table II lists the sensors used for continuous monitoring of the vital data.

TABLE II. SENSORS AND THE ASSOCIATED MEASURING INTERVAL FOR DATA ACQUISITION, WHICH ARE USED TO DETERMINE THE HYDRATION STATUS

| Sensor (company) | Vital Sign | Measuring frequency |
|---|--|---------------------|
| Body Scale (Omron BF 511) | Body weight | Every 30 Minutes |
| Pulsoxymeter (Pulox PO-400) | Pulse | 1 Hz |
| Pulsoxymeter (Pulox PO-400) | Oxygen saturation | 1 Hz |
| Skin conductance sensor (Mindfield eSense) | Skin conductance | 5 Hz |
| Infrared Thermometer | Body temperature | 3x per day |
| Elecctrromagnetic wave sensor (senetics healthcare group GmbH & Co. KG) | Reflection frequency, amplitude, phase | 0.1 Hz |
| Digital blood pressure monitor (Omron-M500) | Blood pressure | 3x per day |

The focus is on the continuously measured vital signs - pulse, oxygen saturation, skin conductance and skin moisture. Fig. 1 shows how the technical equipment is attached to the participant.



Figure 1. Technical equipment for data acquisition during monitoring of vital signs [6].

The Pulox PO-400 pulse oximeter is used to measure oxygen saturation and pulse rate. For this purpose, a finger clip is placed on the left thumb, which in turn is connected to a wrist band. In the Finger clip there is a photoplethysmography sensor, which radiates into the finger with a red ($\lambda = 660\text{nm}$) and a near infrared ($\lambda = 880\text{nm}$) photodiode on the upper side of the fingertip and detects the transmitted light on the lower side with a photodiode sensitive to all wavelengths. The wristband contains the power supply and the memory of the wearable.

The Mindfield eSense wearable is used to measure skin conductance. The skin conductance is measured by two gel electrodes on the base members of the forefinger and middle finger. Moisture can diffuse through the gel in the electrodes into the epidermis, especially during long-term measurements. This would falsify the measurement, so the gel was removed before application. The Mindfield eSense can be used for data collection due to its high measuring interval. The measuring frequency here is 5 Hz.

The microwave antenna sends electromagnetic waves with a frequency of essentially 3 GHz into the body at regular intervals. These waves are absorbed and reflected by the tissue. The reflecting signal is picked up by a network analyzer and is calculated there. The determined scattering parameter includes the values frequency, amplitude and phase. This innovative technology has already been used in a clinical study to analyze skin moisture [7]. The measuring frequency here is 0.1 Hz.

C. Calculation of the Total Body Water

In the first step of signal processing, the determined sensor data are calculated in an algorithm. For this purpose, the personal data are included in (1). This algorithm for sensor fusion calculates the Total Body Water (TBW).

$$TBW = K_1 + K_2 \frac{f}{f_{ref}} + K_3 \frac{rh}{rh_{ref}} + K_4 \frac{SpO_2}{SpO_2_{ref}} + K_5 \frac{p}{p_{ref}} + K_6 \frac{s}{s_{ref}} + K_7 \frac{a}{a_{ref}} \quad (1)$$

f: frequency of the electromagnetic wave

rh: relative skin humidity with skin conductance

SpO₂: oxygen saturation

p: pulse

s: phase of the electromagnetic wave

a: amplitude of the electromagnetic wave

In the second step, the calculated Total Body Water is compared with the real Total Body Water, which was recorded over the day using a personal scale.

The measured values are calculated by sensor data fusion and the total body water is determined. The summand K_1 represents the TBW of the participants in the euhydrated state. This parameter is determined by data acquisition within the scope of the reference day in a gender-specific approach using (2) and (3) [8]:

$$TBW_{man} = 2.447 - (0.09156 * A) + (0.1074 * H) + (0.3362 * M) \quad (2)$$

$$TBW_{woman} = -2.097 + (0.136 * H) + (0.2466 * M) \quad (3)$$

- A: Age
 H: Body height
 M: Body weight

K_2 - K_7 are person-specific weighting factors, which are defined in a calibration phase. These factors determine the influence of the parameters on hydration. During calibration, the parameters are correlated with the actual weight of the participants. The stronger the parameter correlates with the weight, the sooner it is included in the calculation of the total body water. In addition, this parameter includes a compensation factor which takes into account the dimensioning and reproducibility of the factors. This is relevant, as the vital signs are also partly dependent on other environmental factors. Finally the correlation between the measured weight change and vital data is determined. The correlation coefficients are divided into three levels. Correlation coefficients above 0.70 or below -0.70 will be evaluated as strong correlation. Medium correlations are $\pm 0.70 > R > \pm 0.30$. Coefficients with $R \leq \pm 0.30$ will be evaluated as no correlation. We expect medium to strong correlation for the selected vital data.

III. RESULTS

A. Correlation Coefficients at Consecutive Observations

Table III shows the correlation coefficients of the participant 3. All participants are referred with the help of identification numbers to ensure data protection. The code is composed of the number of participants, the number of days used to collect the data and the sex.

TABLE III. CORRELATION COEFFICIENTS OF THE VITAL DATA AND THE TOTAL BODY WATER OF PARTICIPANT 3

| Observation | a [-] | f [-] | rh [-] | s [-] | p [-] | SpO2 [-] |
|---------------------|---------------|---------------|---------------|---------------|---------------|---------------|
| P_3.1 (m) | + 0.68 | - 0.73 | + 0.86 | + 0.11 | - 0.27 | + 0.68 |
| P_3.2 (m) | + 0.50 | - 0.13 | - 0.86 | - 0.60 | - 0.72 | + 0.65 |
| P_3.3 (m) | + 0.46 | - 0.14 | - 0.08 | + 0.25 | - 0.64 | + 0.66 |
| P_3.4 (m) | + 0.93 | - 0.88 | + 0.57 | + 0.55 | - 0.31 | + 0.53 |
| P_3.5 (m) | + 0.81 | - 0.68 | - 0.78 | + 0.76 | - 0.80 | + 0.88 |
| Mean P_3 (m) | + 0.68 | - 0.51 | - 0.06 | + 0.21 | - 0.55 | + 0.68 |

Strong correlations are displayed in dark grey. Medium correlations are presented in light gray. Weak to no correlations are not highlighted. Code P_3.4: P: participant; 3: participant number; 4: day 4.

Participant 3 was monitored over several days. The correlation coefficients reveal mainly moderate and strong correlations of parameters with weight. The vital signs correlate in the same direction for 4 of the 6 parameters. Positive correlations were found for the parameters amplitude and oxygen saturation. This means that the parameters decrease with increasing dehydration. The parameters pulse and frequency of the microwave sensor show a clear negative correlation. This means that the parameters increase with rising dehydration. The parameters skin conductance and phase of the microwave sensor correlate on different days in different directions.

For example, the skin conductance correlates on day 1 with $R(P_{3.1}, \text{skin conductance}) = + 0.86$ in positive direction and on day 2 with $R(P_{3.2}, \text{skin conductance}) = - 0.86$ in negative direction. By averaging the correlation coefficients over the different days, this is clearly shown by the fact that no correlation can be seen for the parameters skin conductance and phase within this investigation.

B. Correlation Coefficients of Different Test Persons

Table IV lists the correlation coefficients of participants one to six. Participant 3 was measured for several times. The table therefore shows the mean value of the correlation coefficients.

TABLE IV. CORRELATION COEFFICIENTS OF THE VITAL DATA AND THE TOTAL BODY WATER OF THE PARTICIPANTS 1 TO 6

| Observation | a [-] | f [-] | rh [-] | s [-] | p [-] | SpO2 [-] |
|--------------|--------|--------|--------|--------|--------|----------|
| P_1.1 (w) | + 0.83 | - 0.80 | + 0.05 | + 0.50 | - 0.87 | + 0.80 |
| P_2.1 (w) | + 0.45 | - 0.41 | - 0.83 | - 0.13 | - 0.88 | - 0.07 |
| Mean P_3 (m) | + 0.68 | - 0.51 | - 0.06 | + 0.21 | - 0.55 | + 0.68 |
| P_4.1 (m) | - 0.07 | + 0.78 | + 0.48 | + 0.78 | + 0.08 | - 0.56 |
| P_5.1 (w) | + 0.86 | - 0.77 | + 0.39 | - 0.72 | + 0.04 | + 0.55 |
| P_6.1 (m) | + 0.36 | + 0.56 | - 0.41 | - 0.75 | + 0.33 | 0.00 |

Participant 3 was observed for several times. For participant 3 is shown the mean value of table 3. The correlation coefficients are divided into three levels. Strong correlations are displayed in dark grey. Medium correlations are presented in light gray. Weak to no correlations are not highlighted. Code P_2.1: P: participant; 2: participant number; 1: day 1.

Table IV reveals that the parameters show a strong correlation but in opposite directions. At least one opposite correlation can be observed for each parameter. In the case of amplitude, for example, this is the case for P_4.1 with $R(P_{4.1}, \text{amplitude}) = - 0.07$. The parameter skin conductance is noticeable in the correlation coefficients shown in Table IV, since in half of the cases they correlate in completely opposite directions. In Addition, Table III show that the skin conductance does not correlate in the same direction even after several measurements at the same person. The pulse also shows a negative correlation in 3 of 6 persons. In two cases there is no correlation ($R \leq \pm 0.3$) and only one data set shows a medium positive correlation ($R > \pm 0.3$). In three of six participants, a negative medium correlation was detected ($R(P_{1.1}, P_{2.1}, \text{Mean P}_3, \text{pulse}) > - 0.55$). This complex situation is also given for the phase of the microwave sensor, as for the oxygen saturation. The frequency of the microwave sensor revealed also correlations in opposite directions. The difference is, that there are only correlation coefficients $R > \pm 0.3$.

C. Comparison between Sexes

Table V demonstrates the differences in the correlation of vital signs and weight between men and women. During the observation 3 women and 3 men were monitored. By averaging the correlation coefficients of the women and separately those of the men, gender-specific deviations are shown.

TABLE V. MEAN OF CORRELATION COEFFICIENTS OF THE VITAL DATA AND THE TOTAL BODY WATER OF THE PARTICIPANTS 1 TO 6

| Observation | a [-] | f [-] | rh [-] | s [-] | p [-] | SpO2 [-] |
|-------------|--------|--------|--------|--------|--------|----------|
| Mean (m) | + 0.32 | + 0.28 | 0.00 | + 0.08 | - 0.05 | + 0.04 |
| Mean (w) | + 0.71 | - 0.66 | - 0.13 | - 0.12 | - 0.57 | + 0.43 |

The correlation coefficients are divided into three levels. Strong correlations are displayed in dark grey. Medium correlations are presented in light gray. Weak to no correlations are not highlighted.

It is noticeable that in all parameters the correlation coefficients of women are on average higher than those of men. For example the pulse show a correlation of $R(\text{Mean (m), pulse}) = -0.05$ for men and $R(\text{Mean (w), pulse}) = -0.57$ for women. For men there are no correlations detectable in five of six parameters. Only the mean value of the amplitude of the microwave sensor shows a moderate positive correlation of $R(\text{Mean (m), amplitude}) = +0.32$ with the weight. For women there are moderate correlations detectable for the frequency of the microwave sensor, pulse and oxygen saturation as well as a strong correlation for the amplitude of the microwave sensor. Nevertheless the two parameters skin conductance and phase of the microwave sensor do not reveal any correlation.

D. Evaluation of Total Body Water

By using the equation (1) the TBW can be calculated from new data sets of vital signs. Fig. 2 shows a representative calculation of the Total Body Water. The total body water of a person is plotted for a period of 8 hours office routine. The total body water was recorded by 30-minute weight checks.

Fig. 2 clearly shows that the total body water of the participant can be calculated using the specified equation.

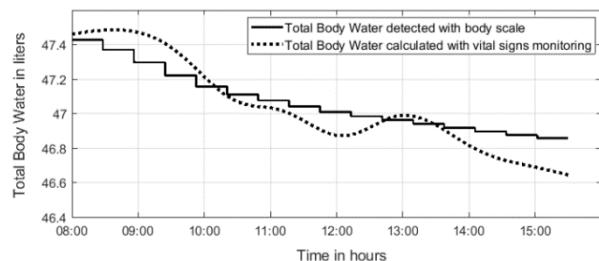


Figure 2. Total body water from participant 3 whereas daily activity measured with body scale and calculated with vital signs monitoring [6].

Participant 3 loses about 600 ml of his total body water during daily office work. This corresponds to a degree of dehydration of about 2 %. However, it should be noted that the equation did not produce representative results for all participants and the determination of the TBW was not possible in all cases.

IV. DISCUSSION

Medium to strong correlations between the vital signs and the weight of the participants were found. Therefore, it was possible to determine parameters which can contribute to the calculation of the total body water. A closer look revealed that the parameters are strongly person specific.

Parameters such as skin conductance show correlations in the opposite direction. This is the case for different participants (according to Table IV) as well as with the data acquisition of a participant over several days (according to Table III). In this observation, it can be expected that the skin conductance will decrease with fluid loss in the skin [10]. However, this cannot be seen in 3 out of 6 persons. This indicates that the correlation of the parameters is strongly dependent on person and additionally on environmental factors. For example, it can be assumed that the skin conductance value is influenced by daily or weekly routines, such as sport exercise or stress. The phase of the electromagnetic wave also shows a similar course as for skin conductance.

A negative correlation between pulse and weight was expected. This means that the pulse increases with dehydration. An increase in pulse rate due to dehydration was already demonstrated in the literature for older people [11], [12]. In two cases there is no correlation ($R \leq \pm 0.3$) and only one data set shows a weak positive correlation ($R > \pm 0.3$). In three of six participants, a negative correlation was detected ($R(P_{1.1}, P_{2.1}, \text{Mean } P_{3.1}, \text{pulse}) > -0.55$). The pulse, for example, is not only influenced by dehydration, but also by factors such as excitement or stress. This influences the reproducibility. Here, it can be assumed that it is also strongly dependent on environmental influences, such as movement. In this case, the parameter can be used with care to monitor dehydration.

The results in table 4 show that due to the small number of samples, it is not possible to draw significant conclusions on the quality of the parameters with regard to the influence of the change in total body water. Therefore, more tests with a focus on influencing variables must be carried out in the further procedure in order to collect representative data and, as a result, to optimize the calculation of the TBW.

For determination of the total body water it was decided on a person-specific basis, which parameters contribute to the calculation. All parameters with at least moderate correlations were contributing to the calculation of the total body water.

Analysis of gender specific mean values revealed that due to the clearer correlations (according to Table V) in women, monitoring of TBW could work better than in men. This means that more parameters can be used to monitor hydration. In women the parameters skin conductance and phase of the microwave sensor revealed no correlation. For men, one parameter (amplitude) showed a moderate correlation. This suggests that women have a fundamentally different water balance than men. It is known that women have a lower fluid balance than men, especially in terms of fluid intake needs [13]. Nevertheless, difficulties can occur if the woman loses additional fluid due to menstruation. However, the men provided a better agreement between calculated total body water and total body water detected by personal scale.

The testing of the algorithm in this specific environment shows in Fig. 2 that it is possible to determine the Total Body Water. However, a very strict calibration of the system is necessary in order to interpret the course of the

vital signs. Due to different correlation directions, it is necessary to determine a person specific parameter set, which is included in the calculation of the TBW.

According to the literature, measurement using a normal personal scale is a cost-effective, fast and representative method [5], but it only allows the determination of total body water in stages. The shift of body fluids between the compartments cannot be considered here.

V. CONCLUSION

The technology for analyzing the hydration status is based on the monitoring of different vital signs. With the help of seven participants the evaluation of the total body water could be performed. Correlations between vital signs and the total body water show that it's possible to measure the hydration status via this technology. However, a person-specific calibration is necessary. In addition, further investigations must be carried out to analyze influencing factors.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Jana Viehbeck conceptualized the data acquisition and the data evaluation. Jana Viehbeck is responsible for draft writing, publishing and correspondance. Michael Wiehl contributed with data analysis and draft writing. Paul Jarvers supported with data acquisition and data analysis. Rainer Brück had approved the final version.

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