Dehydration and Rehydration Monitoring Through Ultrasound Imaging of the Inferior Vena Cava

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***Abstract*—Human hydration level is usually assessed by employing invasive methods, like blood sample analysis, or through time-consuming laboratory techniques, such as urine analysis. This study aims to determine whether changes in the inferior vena cava (IVC), assessed through ultrasound (US) imaging, can be an alternative approach for assessing the hydration level of the user. For this purpose, 29 healthy young subjects (15 females and 14 males) were enrolled in an experimental protocol designed to induce dehydration through moderate-intensity physical activity and subsequent rehydration. During the dehydration phase, US videos of the longitudinal section of the IVC were collected at approximately 10-minute intervals, for a total of five recordings. During the rehydration phase, the videos were captured every 2 minutes, with three recordings conducted. The IVC's diameter and the caval index (CI) were estimated from the US videos during both the dehydration and rehydration phases. Participants' weight was measured in each sub-phase of the dehydration stage. An amount of water equivalent to the weight loss was administered during the rehydration phase. Results show a significant decrease in the IVC's diameter from 30 minutes of activity onwards, compared to the initial diameter ($p < 0.05$), and a return to the baseline condition after 4 minutes of water intake ($p < 0.05$). No significant differences were identified in the CIs across the whole protocol. Further studies are needed to expand the available dataset and identify potential confounding factors that can impact on our approach.**

***Keywords*—Ultrasound Imaging, Inferior Vena Cava, Hydration, Dehydration, Rehydration**

I. INTRODUCTION

Water makes up approximately 50-75% of an adult's body weight, with 65% of the total water found within cells and 35% located in the extracellular space [1]. Maintaining a correct level of hydration is fundamental for preserving the total body water (TBW), especially when performing physical activity. Indeed, during this condition, body heat is dissipated through sweat, a substance primarily composed of water and minerals [2]. It is worth noting that during intense and prolonged physical activities in a very hot and humid environment, sweat production can reach up to 3 *L/hour* [2], underlying the necessity for an adequate TBW. Notably, a decrease in TBW may have severe consequences like cardiovascular fatigue, hyperthermia, reduced performance (physical and cognitive), cramps, and in extreme cases, death [3], [4], [5].

As mentioned before, heat is dissipated through sweat to prevent overheating and maintain a steady internal temperature. In this regard, evaporation is the most efficient cooling mechanism for the human body. The process of sweating is initiated by the release of hormones from the thermoregulation centre that makes the sweat glands absorb water and other substances from the plasma, which constitutes up to 55% of blood and is composed of 90% water, electrolytes, proteins, and nutrients [2].

Currently, the hydration level is assessed using invasive methods like blood sample analysis or time-consuming laboratory techniques such as urine analysis. This highlights the need for rapid, non-invasive approaches, such as imaging techniques, to estimate hydration levels. In this context, an effective approach could involve using ultrasound (US) videos of the inferior vena cava (IVC), which is valuable for predicting fluid responsiveness and for assessing intravascular volume status in various clinical settings [6].

Given the IVC's role in the human circulatory system by transporting blood from the sub-diaphragmatic regions to the heart, accounting for approximately 80% of the venous return [2], with this study, we explore whether tracking the changes of the IVC can be a sensitive methodology for monitoring the hydration level of the user. To do so, we examine how dehydration and subsequent rehydration affect the IVC's size during moderate-intensity physical activity through US videos.

II. MATERIAL AND METHODS

A. Participants

For this study, 29 participants (15 females and 14 males, 23.79 $\pm$ 2.00 years old, height 168.86 $\pm$ 0.08 cm, and weight 62.63 $\pm$ 11.39 kg, with values reported as mean $\pm$ standard deviation) were enrolled. To ensure that the volunteers were in the most homogeneous conditions possible, they were asked to consume at least two litres of water and refrain from smoking and alcohol intake on the day preceding that of the experiment. Participants were instructed to present themselves in a fasting state for a minimum of two hours, to prevent excessive blood flow to the digestive organs located near the IVC. The study was conducted following the Declaration of Helsinki and was approved by the Ethical Committee of Politecnico di Torino (Approval number: 41392/2024). All the participants signed an informed consent form before the beginning of the experiment.

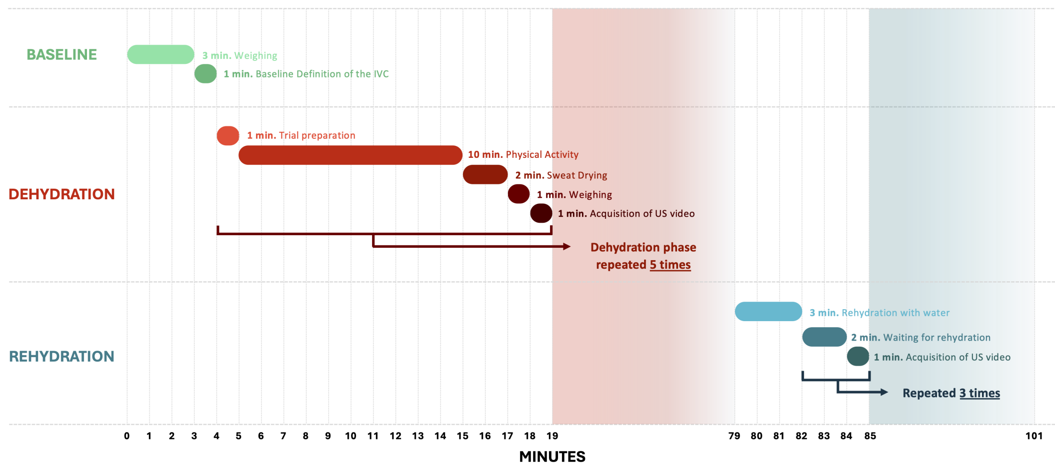

Fig. 1: Graphical representation of experimental protocol adopted for this study, which was divided into three phases: baseline, dehydration and rehydration. The duration of each subphase is reported in the figure along with a brief description of the conducted activity. Notably, the dehydration phase was repeated 5 times, whereas the rehydration was repeated 3 times. The protocol took approximately 100 minutes.

B. Materials

To simulate a moderate-intensity physical activity scenario, a Reharunner 02 (Chinesport S.p.A, Italy) treadmill was used. The participant's weight, which was assessed throughout the experiment without wearing the shoes, was measured using a high-resolution body weight scale (G&GPSE-150, resolution of 20 *g*). US videos were acquired through the MicrUs Ext-1H system using a convex probe C5-2R60S-3 (Telemed Medical Systems s.r.l) ensuring a frame rate of 19 ± 1.94 (mean $\pm$ standard deviation). The US device was connected to a workstation (Intel i7-8850, 2.6 GHz GPU, 32 GB RAM) via a USB port, and the ECHO WAVE II (version 4.3.0) was used as US system management software. The vein tracking was performed through the proprietary software by VIPER s.r.l. In this regard, the reader is referred to [10] for further details about the algorithm implementation.

C. Experimental protocol

Participants underwent a protocol involving the acquisition of US videos of the IVC before and after performing moderate-intensity physical activity on the treadmill. The participants were dressed in athletic attire, comprising a T-shirt and shorts. The steps of the experimental protocol are shown in Fig. 1 and consisted of three phases: baseline, dehydration (DH) and rehydration (RH), represented in green, red, and blue, respectively. During the initial phase, the participant's weight was measured, and a US video of the IVC in a longitudinal view was recorded while the participant was in a supine position. This served as a reference for future comparisons. All US scans (this and subsequent ones) were obtained with a subxiphoid approach, with the subject lying supine on a medical couch, during normal breathing.

The DH phase was composed of a preparation step, in which the participant could remove the gel residuals from the previous phase, and a 10-minute walk on the treadmill with an inclination of 10 % and a speed of 5 *km/h*. After that, the sweat was dried off with a towel, and the weight was assessed again, along with the US video. These steps of the dehydration phase were repeated 5 times.

Finally, during the RH phase, we asked the participant to intake the amount of water lost during the dehydration phase, estimated as the total weight loss during the DH phase to the baseline. Notably, we assumed that the weight loss was solely due to sweat, as the participants were unable to change clothes or use the restroom for the whole duration of the protocol. Water was drunk once, and then the US acquisition was repeated 3 times, every 2 minutes. Between the video's acquisitions, subjects were asked to sit down to avoid any redistribution of blood, which would have caused incorrect measurements.

D. IVC Segmentation

As shown in Fig. 2, the used vein tracking software allowed the extraction of the diameter in real time for each frame. Moreover, the algorithm tracked the same portion of IVC over time to mitigate the effects of drifts that can impact the IVC diameter evaluation [7], [8], [9]. The IVC edges were estimated by sampling along 21 directions intersecting the blood vessel, and then averaging it to obtain a single resilient value of diameter for each frame.

Among the features that can be automatically extracted from the segmented US videos, we focused on the diameter of the vessel and the Caval Index (CI), defined as:

$$CI(t) = \frac{D_{max}(t) - D_{min}(t)}{D_{max}(t)} \tag{1}$$

where $D_{max}(t)$ is the interpolation of the local maxima of the diameter over time and $D_{min}(t)$ is the interpolation of the minima. By interpolating each maximum and minimum, it was possible to estimate the CI for each frame more robustly. Given its definition, CI ranges between 0 and 1.

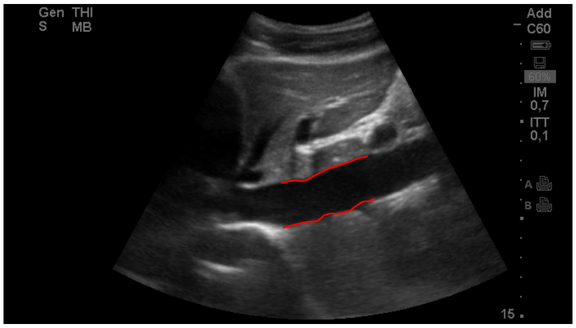

Fig. 2: Longitudinal section of the IVC from one participant. The estimated contours obtained through the VIPER algorithm are highlighted in red.

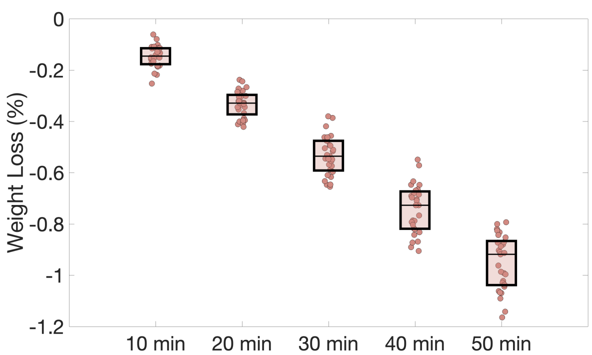

Fig. 3: Weight loss from the baseline condition expressed as a percentage for all the sub-phases of the dehydration phase: 10, 20, 30, 40 and 50 minutes, respectively. Notably, each dot represents a subject.

E. Statistical Analysis

Statistical analyses were performed using MATLAB® (R2024a, MathWorks, Inc.). To assess differences across the protocol's phases, a one-way repeated measures ANOVA was conducted on log-transformed data to account for potential deviations from normality. Sphericity was evaluated using Mauchly's test, and the normality of residuals was assessed with the Lilliefors test. When sphericity was violated, the Greenhouse-Geisser correction was applied. Significant effects revealed by the ANOVA were followed by post hoc pairwise comparisons using paired t-tests. For all analyses, the significance threshold (α) was set at 0.05.

III. Results and Discussion

As expected, participants showed weight loss during the DH phase (see Fig. 3). After 50-minutes from the beginning of the experiments, participants showed a reduction in their weight between -0.8 and -1.2 %, thus suggesting that the chosen experimental protocol was able to reproduce the water loss typically occurring with moderate physical activity.

Continuous signals representing the variation in IVC diameter and CI over time can be appreciated in Fig. 4. Notably, Fig. 4A considers the IVC's diameter of one participant in a temporal window of 18 s during three different conditions:

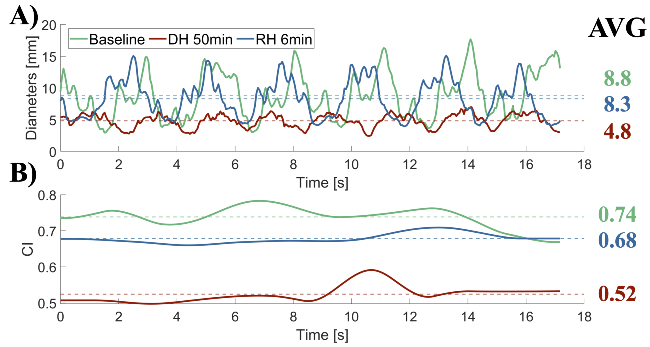

Fig. 4: **A**) Temporal dynamic of the IVC's diameters for one subject involved in the protocol during the baseline, dehydration (DH) at 50 minutes, and rehydration (RH) at 6 minutes. To facilitate a comparison between the conditions, the average (AVG) diameters were estimated and reported on the right part. **B**) Similar to A) but considering the Caval Index (CI).

baseline, DH at 50-minutes, and RH at 6-minutes. Similarly, Fig. 4B shows the changes in the CI for the same subject. To facilitate a comparison between signals, the average values were estimated and reported on the right part of the Figure. As expected, during DH, the diameter was lower than at baseline and RH conditions, thus suggesting a lower level of hydration in this case. In this case, the CI is also lower during DH, which contradicts our expectations. The emptier the vein, the more it should collapse during breathing and vice versa.

The previous analysis was then extended to all the participants by estimating the average diameters and CIs during each step of the protocol. Results are reported in Fig. 5 and Fig. 6, investigating the average diameter and CI, respectively. Due to the violation of sphericity in the data, the Greenhouse-Geisse correction ($\epsilon = 0.66$) was applied to the ANOVA for the diameter and the CI over time. A significant effect of time was obtained for the diameter (with $p < 0.05$); no significant effect was highlighted for CI over time. With particular reference to Fig. 5, it is possible to appreciate the decreasing trend in the DH phase for the average diameters from the baseline, with significant differences starting from 30 minutes ($p < 0.01$). For what concerns the RH phase, results indicate that after 4 minutes from the water intake, the average diameter of the IVC was significantly different ($p < 0.01$) compared to the 50-minutes condition (dehydration). Furthermore, at the 4-minute mark, the statistical difference from baseline disappeared, indicating that all participants had achieved a level of hydration similar to the beginning of the experiment. It is important to emphasize that paired comparisons were conducted across all sub-phases. Specifically, for the DH phase, Fig. 5 highlights in bold the post hoc significance markers, indicating pairs that exhibit a significant difference relative to the Baseline. This evidence suggests that the IVC size is influenced by fluid loss due to sweating. Conversely, during the RH phase, Fig. 5 emphasizes in bold the markers that identify significant differences between the 50-minute (dehydrated) condition and the subsequent RH phase, supporting the conclusion that the

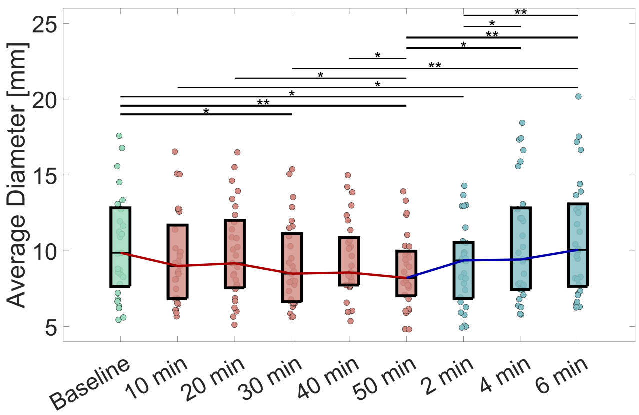

Fig. 5: Boxplot representing the average IVCs' diameter across all subjects during the baseline (green), DH (red), and RH (blue) phases. One red and blu lines connecting the median values of the distributions are included as well, relative to the DH and RH phases, restively. Each dot represents a subject. Statistically significant differences are indicated with * and **, for $p < 0.05$ and $p < 0.01$, respectively.

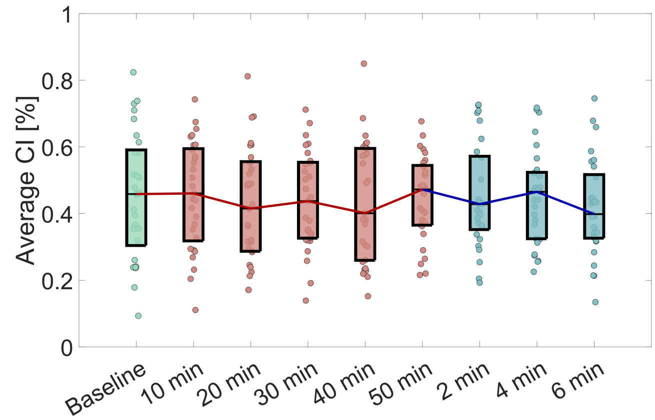

Fig. 6: Boxplot illustrating the mean CI across all subjects during the baseline (green), DH (red), and RH (blue) phases. The median values of the boxplot during baseline and at 50 minutes were interpolated. The interpolation line was also computed between 50 and 6 minutes.

IVC diameter is affected by the reintroduction of water.

For what concerns the CI, whose dynamic is represented in Fig. 6, no statistical differences were detected during all the phases of the protocol. It was probably not possible to measure accurately a sensitive parameter such as CI under our experimental conditions, which involved large variations in the subjects' condition related to fatigue and its many physiological responses (including increased heart rate and respiratory effort, directly affecting IVC dynamics).

Overall, the obtained results are consistent with previous studies investigating similar conditions but with less frequent US video acquisitions [11], [12].

IV. CONCLUSION

Conventional methods for assessing hydration status are frequently invasive, labour-intensive, and impractical for dynamic scenarios such as athletic performance. Through a comprehensive examination of the dehydration and rehydration processes in the human body, we devised a protocol utilizing US imaging of the IVC to assess the hydration state of the participants. The preliminary results presented in this paper show the correlation between IVC diameter and the individual's hydration level, thus suggesting that this approach may work as an alternative to traditional techniques. However, great individual variability was observed.

This study paves the way for further research to better understand the physiology underlying the process of dehydration and rehydration without the use of invasive measurements. Moreover, additional studies are required to extend the available dataset and investigate potential confounding factors to better understand the goodness of the presented approach.

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REFERENCES

[1] Schloerb, P., Friis-Hansen, B., Edelman, I., Solomon, A. & Moore, F. The measurement of total body water in the human subject by deuterium oxide dilution; with a consideration of the dynamics of deuterium distribution.. *The Journal Of Clinical Investigation*. **29** **10** pp. 1296-1310 (1950)

[2] Stanfield, C. Principles of human physiology. (Pearson,2012)

[3] Grandjean, A. & Grandjean, N. Dehydration and cognitive performance. *Journal Of The American College Of Nutrition*. **26**, 549S-554S (2007), http://dx.doi.org/10.1080/07315724.2007.10719657

[4] Copping, J. & Gisolfi, C. Thermal effects of prolonged treadmill exercise in the heat. *Medicine & Science In Sports & Exercise*. (1974)

[5] Montain, S. & Coyle, E. Benefits of fluid replacement with carbohydrate during exercise. *Medicine & Science In Sports & Exercise*. (1992)

[6] Zhang, J. & Critchley, L. Inferior Vena Cava ultrasonography before general anesthesia can predict hypotension after induction. *Anesthesiology*. **124**, 580-589 (2016), http://dx.doi.org/10.1097/aln.0000000000001002

[7] Policastro, P. & Mesin, L. Estimation of inferior Vena Cava size from ultrasound imaging in X-plane. *Electronics*. **13**, 3406 (2024), http://dx.doi.org/10.3390/electronics13173406

[8] Policastro, P., Ermini, L., Civera, S., Albani, S., Musumeci, G., Roatta, S. & Mesin, L. Effect of respirophasic displacement of the inferior Vena Cava on size measurement in 2-D ultrasound imaging. *Ultrasound In Medicine And Biology*. **50**, 1785-1792 (2024), http://dx.doi.org/10.1016/j.ultrasmedbio.2024.07.005

[9] Mesin, L., Giovinazzo, T., D'Alessandro, S., Roatta, S., Raviolo, A., Chiacchiarini, F., Porta, M. & Pasquero, P. Improved repeatability of the estimation of pulsatility of inferior Vena Cava. *Ultrasound In Medicine & Biology*. **45**, 2830-2843 (2019), http://dx.doi.org/10.1016/j.ultrasmedbio.2019.06.002

[10] Mesin, L., Pasquero, P. & Roatta, S. Tracking and monitoring pulsatility of a portion of inferior vena cava from ultrasound imaging in long axis. *Ultrasound In Medicine & Biology*. **45**, 1338-1343 (2019)

[11] Waterbrook, A., Shah, A., Jannicky, E., Stolz, U., Cohen, R., Gross, A. & Adhikari, S. Sonographic Inferior Vena Cava Measurements to Assess Hydration Status in College Football Players During Preseason Camp. *Journal Of Ultrasound In Medicine*. **34**, 239-245 (2015), https://onlinelibrary.wiley.com/doi/abs/10.7863/ultra.34.2.239

[12] Ragaisyte, E., Bardauskiene, L., Zelbiene, E., Darginavicius, L., Zemaityte, E., Jasinskas, N. & Stasaitis, K. Evaluation of volume status in a prehospital setting by ultrasonographic measurement of inferior vena cava and aorta diameters. *Turkish Journal Of Emergency Medicine*. **18**, 152-157 (2018), https://www.sciencedirect.com/science/article/pii/S2452247317302443