

Short-Term Segmental Bioimpedance Alterations During 6° Head-Down Tilt

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Abstract—As missions in space increase in duration and distance from Earth it is critical to understand the impact that exposure to microgravity has on the health and potential performance of crews. Segmental bioimpedance measurements can track resistances changes in tissues that result from fluid redistribution and could be a tool for continuous fluid shift monitoring in microgravity. In this work, the range of segmental (legs, arms, torso, and neck) 10 kHz and 100 kHz resistances and their relative changes during 4 hours of 6° head down tilt are reported as well as the observed resistance differences between left/right body segments throughout the protocol.

I. INTRODUCTION

Conditions experienced by astronauts during space travel include high radiation exposure and micro-gravity [1]. These represent extreme conditions compared to those at the Earth's surface and cause a range of adaptations in the human body [1]. As missions in space increase in duration and distance from Earth, it is critical to understand the impact of extreme conditions on crew health and performance and to develop appropriate counter-measures. Focusing on micro-gravity, this condition causes fluid redistribution to occur due to the removal of the hydrostatic gravitational gradient. Without this gradient, fluid moves from the legs towards the chest and head [2]. These fluid shifts impact multiple aspects of the body (cardiovascular system, reflex mechanisms, endocrine mechanisms, vision) [1]. In fact, microgravity is associated with reduced near vision in approximately 23% of astronauts after a few days of exposure, with 48% with near sight vision decreases after long-duration missions to the international space station [3].

In support of monitoring fluid shifts within the human body the passive electrical impedance of tissues (often referred to as tissue bioimpedance) has been investigated as a non-invasive approach [4]–[7]. Tissue bioimpedance is related to the tissue fluid, type, structure, and geometry. Changes in each feature are expected to alter the tissue impedance and potentially serve as a biomarker of that underlying mechanism of change (e.g. fluid shift, tissue damage, tissue swelling). For fluid shift applications, trends of increasing resistance in body segments with decreasing fluids have been reported [4], [6], [7]. Beyond microgravity induced fluid shifts, tissue bioimpedance is being investigated for health applications that include fluid tracking during dialysis [9], quantifying skeletal muscle fatigue [10], and assessing joint health [11].

While these measurements have been utilized in studies of fluid shifts during emulated microgravity [4], [6] and microgravity [7], the equipment to collect them previously has been portable [8] but not wearable. With the recent availability of commercial sensors with bioimpedance capabilities, there is an emerging opportunity to develop wearable systems [12] to collect tissue bioimpedance continuously for real-time fluid shift monitoring in microgravity environments. This continuous monitoring could advance personalized monitoring of fluid shifts and evaluation of counter-measures. Prior to developing wearables for this application, studies that quantify the expected segmental impedances and their alterations from fluid shifts and potential symmetry differences in fluid redistributions will help inform the design requirements (e.g. required ranges, sampling rates, etc.). That provides the motivation for our preliminary effort, to quantify and compare the segmental tissue impedance alterations that occur in right/left segments of the arms, legs, and torso during 4 hours of emulated micro-gravity (6° head down tilt).

II. METHODS

Bioimpedance measurements from 7 segments (left/right leg, torso, arm and neck) of one participant (Female, 24 years of age, 169 cm, 68.4 kg, 23.9 BMI) were collected at approximately 30 minute intervals over a 4 hour head-down tilt period. The study participant provided their written informed consent to be in the study. This research and its activities were approved by The University of Alabama's Institutional Review Board (UA IRB-19-022-ME). Prior to data collection, the participant fasted for 12-hours and voided their bladder upon arrival at the study facilities. Next, 28 Ag/AgCl electrodes in 7 tetrapolar configurations were fixed to the participant in the locations given in Fig. 1(a) after each site was cleaned with alcohol. A 2 meter cable was used to interface each electrode to the measurement equipment for data collection.

A. Keysight E4990A Impedance Analyzer

Bioimpedance measurements were collected using a Keysight E4990A impedance analyzer (Keysight Technologies, USA) with a multi-site printed circuit board (PCB) interface. The Keysight E4990A utilizes a tetrapolar configuration to apply a controlled sinusoidal current at a fixed frequency using two leads (I+, I-) with the excited voltage across a material or device sensed using an additional two leads (V+, V-). From the voltage and current, the overall impedance was calculated ($Z = V/I$) at each of the discrete measured frequencies. The addition of the interface

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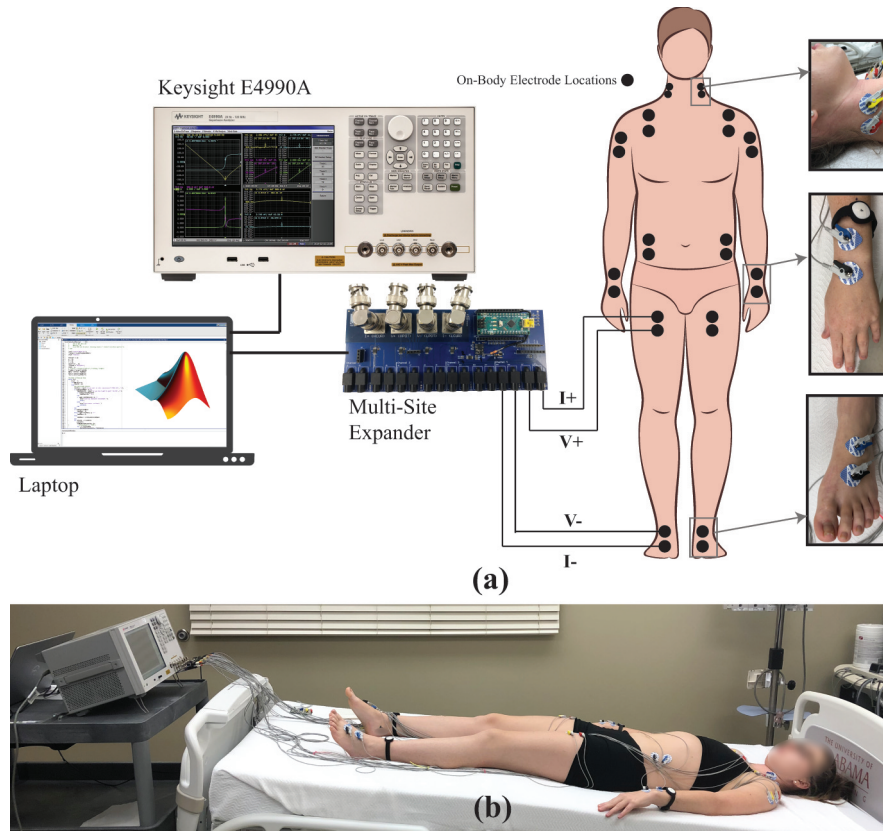


Fig. 1. a) Experimental configuration to collect 7 segmental bioimpedances (right/left arms, legs, torso and neck) from participant using Keysight E4990A with multi-site expander interface and b) sample setup of participant during 6° HDT.

in this study expanded the number of body segments that could be monitored without manual reconfiguration of the leads to the Keysight E4990A. Analog multiplexors were utilized to electronically control the routing of the Keysight E4990A tetrapolar signals (I+, I-, V+, V-) to 1 of 8 sets of mechanical headers. For this study, 7 of the available 8 sets of headers were wired to participant body segments. A sample of cabling from the interface to the electrodes on a leg segment of a participant is given in Fig. 1(a). To compensate for the effects of the interface PCB and wiring, the open/short/load compensation procedure was applied with the Keysight E4990A prior to collection of participant measurements. Both the PCB interface and Keysight E4990A were controlled during data collection by a connected laptop computer (using MATLAB) which automated control of the analog multiplexors for appropriate routing of the test signals, initiated measurement sweeps by the Keysight E4990A (collecting measurements from 1 kHz to 1 MHz), and transferred the collected data to MATLAB for storage and later post-processing.

B. Head Down Tilt Protocol

After interfacing to the measurement equipment, the participant transitioned from standing, to sitting on a hospital bed, to supine on a hospital bed (at 0° incline). A baseline measurement was collected with the participant in this supine position. The hospital bed was then adjusted so the partici-

part experienced a 6° head-down tilt (HDT). A photo of this setup with the participant in supine, HDT position is given in Fig. 1(b). At this point, the first supine measurements were collected (referenced as time 0 minutes in Fig. 2) with measurements collected at 30 minute intervals for 4 hours. After 4 hours, the hospital bed was returned to 0° and the participant slowly transitioned from supine, to sitting, to standing as they were comfortable with a final measurement collected 30 minutes after this positional change. In total, measurements were collected at 11 timepoints during this protocol.

III. RESULTS

While multi-frequency impedance measurements were collected in this study, this initial analysis focuses on the 10 kHz and 100 kHz resistance collected from all body segments. These resistances at each timepoint throughout the protocol are given in Figs. 2(a) and (b), respectively. The resistance component of impedance measurements are attributed to the tissue fluids, with low/high frequency values attributed to extra/intra cellular fluids; which is why this work has focused on resistances at low (10 kHz) and high (100 kHz) frequency. Comparing the resistances of the segments measured, each segment had visually discernible differences (ranked leg, arm, torso and neck from highest resistance to lowest) that showed resistance alterations throughout the protocol from HDT induced fluid redistribu-

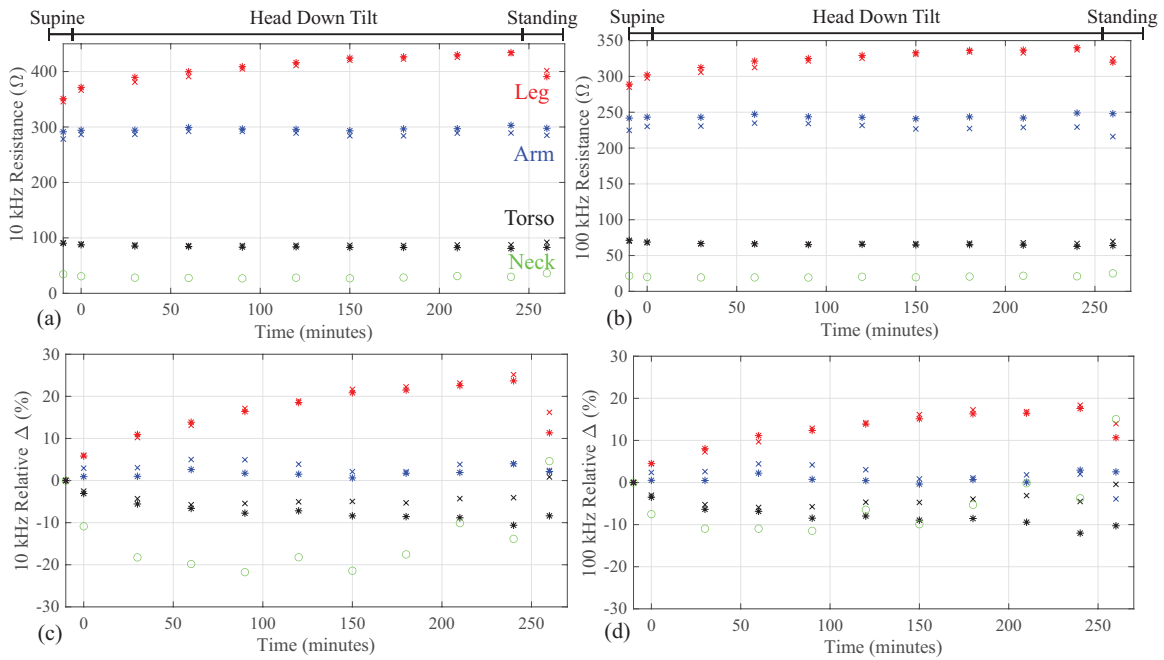


Fig. 2. a) 10 kHz and b) 100 kHz resistance of right (*) and left (x) segmental bioimpedance (arm, leg, torso, neck) of participant throughout the bed-rest protocol and the relative differences of c) 10 kHz and d) 100 kHz resistance compared to baseline.

tion. The range of 10 kHz resistances in Fig 2(a) spanned from 27 Ω to 433 Ω and 100 kHz resistances in Fig. 2(b) ranged from 19 Ω to 337 Ω . To visualize the differences of each body segment in comparison to baseline (collected while the participant was in the supine position) the relative difference of each timepoint compared to this baseline is given in Figs. 2(c) and (d) for 10 kHz and 100 kHz values, respectively. The transition to and time in HDT resulted in an increase in the leg/arm measurements and decrease in the torso measurements that continued for the entire HDT. The greatest resistance alterations occurred in the legs, increasing by 25% after 240 minutes in HDT. While changes in the arms were not as large as the legs, there was still a 3.9% increase by 240 minutes. Both torso and neck had decreases of approximately 11% and 14% by 240 minutes. Comparing the differences between timepoints, the resistance alterations tend to decrease as time in the HDT increases. Focusing on the 10 kHz leg resistance, a change of 4.9% is observed between 0 and 30 minutes with a change of 1.6% between 210 and 240 minutes. The return to 0° supine position, sitting, and standing between 210 and 240 minutes resulted in a reversal of the HDT trends moving back towards their baseline values; indicating a movement of fluid from the torso/neck back to the legs/arms.

IV. DISCUSSION

The results reported for the study participant support that the HDT induced a fluid shift away from the arms and legs towards the torso and neck, which aligns with previous HDT studies of fluid redistribution. Montgomery et. al reported decreases in 50 kHz bioimpedance derived segmental calf, thigh, upper arm, and lower arm volumes

and increases in pelvis and thorax volumes in 12 subjects after 4 hours of 6° HDT [4]. The resistances reported here support the observations of Montgomery et. al, in that the leg segments respond immediately to HDT with a volume decrease (observed as a resistance decrease in this study) that occurs at a consistent rate.

Comparing the two frequencies measured in this study, the same resistance trends over time are observed for the 100 kHz and 10 kHz data. However, the magnitude differences are lower in the 100 kHz resistances than their 10 kHz counterparts. For example, the 100 kHz leg and arm resistances had an increase of 18.2% (compared to 25% at 10 kHz) and 2.0% (compared to 3.9% at 10 kHz), respectively. Often low frequency resistance is attributed to the extra-cellular tissue fluid and high frequency resistance attributed to total tissue fluid (extra-cellular + intra-cellular). Based on this, the differences in resistance at the frequencies reported in Fig. 2 supports that extra-cellular fluid had a greater redistribution (shifting from legs/arms to torso/neck) than intra-cellular fluid during HDT. Fenech and Jaffrin have also previously commented that extra-cellular water will redistribute in response to gravity more quickly than intra-cellular water which was supported by their studies of extracellular and intracellular volume variations during postural changes [5].

While the segmental arm resistances did show a decrease comparing the 0 minute and 240 minute timepoints, across the entire HDT period there were periods when there were $\leq 1\%$ decreases (e.g. 120, 150, 180 minutes). This variation in resistance may indicate that segmental activity during the HDT alters the fluid redistribution. During HDT, the participant was able to adjust their body positioning for

comfort but was not allowed to prop their body up. As a result, the most segmental movement during HDT occurred in the arms in comparison to the legs which may account for the differences in resistance over time if muscle activity countered the fluid redistribution that resulted from HDT. However, this hypothesis (muscle activity counters the fluid shift in the arms) requires further study to quantify the level of activity and the change in resistance to validate.

While fluid redistribution during HDT is expected to be nearly equal in both left/right sides of the body, both were measured during this data-collection session to investigate this assumption for the single participant. The right/left leg, arm and torso resistances and relative differences (compared to supine) at each timepoint in Fig. 2 show good visual agreement but do not overlap perfectly. To further visualize differences between right/left segments, the relative differences between them at each timepoint during the protocol are given in Fig. 3; positive values indicate the right segment impedance was greater than the left, and negative values indicate the left segment impedance was larger than the right. The 10 kHz and 100 kHz right/left relative differences are represented by the symbols '+' and 'o', respectively. The right/left leg measurements had the lowest relative difference ($< \pm 4\%$) across all timepoints, though torso and arm differences exceeded $\pm 5\%$ at timepoints ≥ 210 minutes. While this study was not able to elucidate the reasons for these differences, it does highlight a future area of inquiry and that wearable systems for fluid shift monitoring may need to incorporate additional sensor modalities (i.e. inertial measurements or electromyography) to quantify activity.

A limitation of this study is measurements of only one participant were collected and reported. Data collection from additional participants is required to: **1)** evaluate whether trends in terms of symmetry differences and 10 kHz/100 kHz resistance differences persist across participants with different characteristics (age, body composition, fluid status) and **2)** evaluate the impedance range that should be the focus of wearable systems for fluid shift monitoring. Additionally, only the resistance component of the tissue bioimpedance was explored. Future studies should also investigate the tissue reactance.

V. CONCLUSION

The observed increase of leg/arm segmental resistance and decrease of torso/neck resistance (at 10 kHz and 100 kHz) further support that bioimpedance measurements capture fluid redistribution in segmental tissues. Further, differences at 10 kHz were greater than 100 kHz supporting that differences in extra/intra cellular shifts can also be captured. Alterations between right/left sides of the body may suggest that additional sensor modalities should be paired with bioimpedance sensing to identify both context and impedance changes for real-time fluid shift monitoring. Finally, wearable bioimpedance systems for segmental fluid shift monitoring should be optimized for measurements in the 10Ω to 500Ω range based on the changes observed in this study.

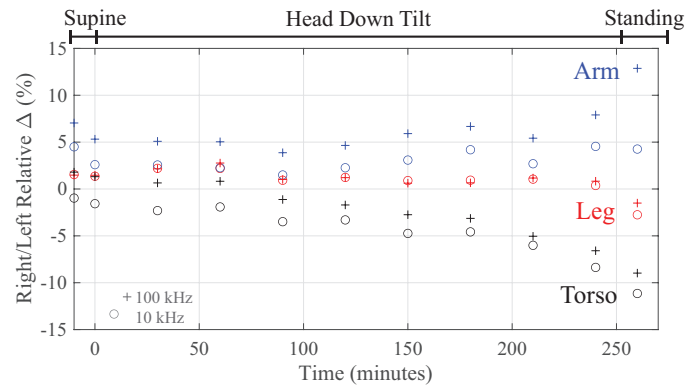


Fig. 3. Relative differences between right/left leg (red), arm (blue), and torso (black) segmental 10 kHz (+) and 100 kHz (o) resistances over protocol duration.

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