Thigh Cuff Effects on Venous Flow Redistribution During 4 Days in Dry Immersion

Philippe Arbeille; Danielle Greaves; Laurent Guillon; Stephane Besnard

PURPOSE: The objective was to quantify the venous redistribution during a 4-d dry immersion (DI) and evaluate the effect of thigh cuffs.

METHODS: The study included nine control (Co) and nine subjects wearing thigh cuffs during the daytime (CU). Ultrasound measures were performed Pre-DI, on day 4 AM (D4 AM) and D4 PM: left ventricle stroke volume and ejection fraction (SV, EF), jugular vein volume (JVvol), portal vein diameter (PV), and middle cerebral vein velocity (MCVv). An additional measure of JVvol was performed on Day 1 after 2 h in DI.

RESULTS: After 2 h in DI, JVvol increased significantly from Pre in both groups, but increased more in the Co compared to the CU subjects (Co: 0.27 ± 0.15 cm^3 to 0.94 ± 0.22 cm^3; CU: 0.32 ± 0.13 cm^3 to 0.64 ± 0.32 cm^3). At D4 AM, SV and EF decreased from Pre (SV: 111 ± 23 cm^3 to 93 ± 24 cm^3; EF: 0.66 ± 0.07 to 0.62 ± 0.07). JVvol was slightly increased (Co: 0.47 ± 0.22 cm^3 CU: 0.35 ± 014 cm^3). MCVv and PV remained unchanged from Pre-DI. No difference was found between the two groups for any of the parameters measured. From D4 AM to PM, no significant change was observed for any parameter.

CONCLUSION: The results confirm that DI induces, during the first 2-3 h, a significant cephalic fluid shift as observed in spaceflight. During this early phase, the thigh cuffs reduced the amplitude of the fluid shift toward the head, but after 4 d in DI there was only a slight memory (residual) effect of DI on the jugular volume and no residual effect of the thigh cuffs.

KEYWORDS: dry immersion, jugular vein, cerebral vein, portal vein.

Arbeille P, Greaves D, Guillon L, Besnard S. *Thigh cuff effects on venous flow redistribution during 4 days in dry immersion*. Aerosp Med Hum Perform. 2020; 91(9):697–702.

Some astronauts reported vision problems during long duration spaceflights onboard the International Space Station (ISS), which has led to the hypothesis that vision problems may be caused by cephalic fluid shifts induced by the absence of gravity. It was suggested that these vision problems could be related to an increased intraocular pressure and/or intracranial pressure. A recent study has provided support for this hypothesis by demonstrating an increase in these two parameters with cephalic fluid shifts induced by head down tilt bed rest. Additionally, that study showed a reduction of these when fluid was shifted away from the head using lower body negative pressure.[10]

Dry immersion (DI) has been proposed as a method of mimicking the effects of microgravity exposure on Earth[15] with various durations of use (10 h to 28 d). During DI, the subject is seated in a semirecumbent position inside a water tank. Bags are used to separate the subject from the water such that the subject skin is not in contact with the water. The subject is submerged up to the neck level with the water pressure on the body and the legs promoting the transfer of interstitial fluid into the vascular system and a total shift of fluid toward the cephalic area.[11,12] During the first 4 h of immersion, cardiac stroke volume has been found to increase[15] and the jugular vein volume to increase significantly.[1] After 1 d, plasma volume has been found to be significantly reduced, with further reductions seen after 3 d.[14] However, there are currently no published data on central or peripheral venous flow changes after the first day in DI. In addition, a knowledge gap exists regarding the use of countermeasures to reduce the cephalic fluid redistribution.

From the Centre de Recherche Coeur et Maladies vasculaires, Tours, France.

This manuscript was received for review in September 2019. It was accepted for publication in June 2020.

Address correspondence to: Professor Philippe Arbeille, Unite Med Physiol Spatiale (UMPS-CERCOM), Faculte de Medecine, 37032 Tours, France; arbeille@med.univ-tours.fr.

DOI: https://doi.org/10.3357/AMHP.5524.2020

The purpose of the current study was to quantify changes in venous volume and flow on the upper body after 1 and 4 d spent in DI, with and without the effect of wearing the Russian "Braslets" countermeasure hardware (also known as thigh cuffs). These cuffs are currently carried by all Russian crew on ISS as part of their personal items and are worn during the day to reduce cephalic congestion symptoms. Previous dry immersion study (without any countermeasure such as thigh cuffs) has shown that after the first day the jugular vein volume (JVvol), middle cerebral vein velocity (MCVv), and portal vein diameter (PV) were significantly increased.[1] We hypothesized: 1) that after 4 d in DI, both the JVvol, MCVv, and PV would again exhibit an increased volume in the control group, similar to what has been observed with spaceflight and head down bedrest;[4,5] and 2) that the thigh cuff countermeasure would mitigate the cephalad fluid transfer, reflected by attenuated changes to the JVvol, MCVv, and PV.

METHODS

Subjects

A total of 18 subjects were included in the study and randomly divided at DI-2 into Control (Co) or Cuffs group (CU) (9/9 split). All subjects were informed about the experimental procedures and gave their written informed consent. The experimental protocol conformed to the standards set by the Declaration of Helsinki and was approved by the local Ethics Committee (CPP Est III: October 2, 2018, no. ID RCB 2018-A01470-55) and French Health Authorities (ANSM: August 13, 2018; Clinical Trials.gov Identifier: NCT03915457). There was no significant difference in any of group characteristics between the groups at baseline (**Table I** and **Table II**).

The study was conducted at the MEDES space clinic, Toulouse, France. The experimental protocol included 4 d of ambulatory baseline measurements before immersion (Dry immersion minus 4 d "DI-4" to Dry Immersion day minus 1 d "DI-1"), 5 d (120 h) of dry immersion (DI1 to DI5), and 2 d of ambulatory recovery (R0, R+1). Subjects randomized to the CU group wore the thigh cuffs during the 5 d of DI, from 10 h to 18 h at DI1 and from 8 h to 18 h at DI2–DI5. Thigh cuffs are elastic straps[9] customized to each subject to have the same effects on lower limb distensibility as at a pressure level of approximately 30 mmHg. Individual adjustment was determined for each subject with calf plethysmography, performed in the supine position at DI-2. General protocol of strict DI was conducted according to methodology detailed in De Abreu et al.[6] Thermoneutral water temperature was continuously maintained. The lights-off period was set at 23:00–07:00. Daily hygiene, weighing, and some specific measurements required extraction from the bath. During these out-of-bath periods, subjects maintained the −6° head-down position. Total out-of-bath supine time for the 120 h of immersion was 9.7 ± 1.3 h. On DI1–DI4 out-of-bath time was 1.1 ± 0.6 h/d. On DI5 out-of-bath time was 5.3 ± 1.1 h, the time required for muscle biopsy and MRI. Otherwise, during DI, subjects remained immersed in a supine position for all activities and were continuously observed by video monitoring. Body weight, blood pressure, heart rate, and tympanic body temperature were measured daily. The frames of adequate water intake were fixed at 35–60 $ml \cdot kg^{-1} \cdot d^{-1}$; within these frames water intake throughout the protocol was ad libitum (measured). The menu composition of each experiment day was identical for all participants and dietary intake was individually tailored and controlled during the study.

Procedure

Ultrasound measurements were performed with the Echograph Orcheo-Lite (Sonoscanner, Paris, France; ISS version: 8.4.101.99) equipped with three motorized and 3D probes. One superficial motorized probe with a linear array transducer (17 MHz) was used for superficial organs and vessels. A cardiac/transcranial motorized probe with a phased array transducer (1.5–3.5 MHz) was used for the heart and intracranial vessels. An abdominal motorized probe with a curved array transducer (3–5 MHz) was used for abdominal organs and vessels. Each probe was positioned over the acoustic window of each organ/vessel, then the operator activated an automated motorized sweep (Tilt ± 45° from vertical to the skin) in order to capture an integrated video loop. In this video, all of the sequential images of the organs under the probe head are included, as well as a 3D reconstruction of the organ. This automated motorized process allowed quick and efficient visualization of the organ in any of the views required for measurement (long, short axis, oblique …).[2]

Cardiac volumes: left ventricle systolic and diastolic volumes were evaluated from the time motion trace (M-mode) taken on the left ventricle parasternal long axis view, right below the mitral valve.[16] Stroke volume (SV) was calculated as: (left ventricle diastolic − systolic volume) and ejection fraction (EF) as: (SV/left ventricle diastolic volume).

Jugular vein volume was measured from both the long axis and short axis views of the right internal jugular vein. Since this vein is an irregular, noncircular 3-dimensional object, an estimate based on the mean of several cross-section areas along the JV long axis was used. The probe

Table I. Baseline Group Characteristics at DI-2H, Mean ± SD.

	AGE (yr)	HEIGHT AT SELECTION (cm)	DI-2H WEIGHT (kg)	DI-2H BMI ($kg \cdot m^{-2}$)	DI-2H Vo_{2MAX} ($mL \cdot min^{-1} \cdot kg^{-1}$)	DI-2H MORNING HR (bpm)	DI-2H MORNING TEMP (°C)	DI-2H MORNING SBP (mmHg)	DI-2H MORNING DBP (mmHg)
Control ($N = 9$)	33.9 ± 7.1	176 ± 6	73.9 ± 7.5	23.9 ± 1.7	46.5 ± 8.1	57 ± 6	36.4 ± 0.3	115 ± 11	68 ± 5
Cuffs ($N = 9$)	34.1 ± 3.7	180 ± 4	74.3 ± 8.8	22.7 ± 1.8	46.9 ± 5.8	58 ± 8	36.4 ± 0.5	117 ± 10	68 ± 9
unpaired *t*-test	$P = 0.93$	$P = 0.08$	$P = 0.91$	$P = 0.16$	$P = 0.91$	$P = 0.6$	$P = 0.71$	$P = 0.78$	$P = 0.92$

Table II. Body Weight and Vo_{2max} Before and at the End of Dry Immersion, Mean ± SD.

	CONTROL		CUFFS	
VARIABLE	BEFORE	END	BEFORE	END
Morning weight, kg (DI1; R0)	73.9 ± 7.5	72.1 ± 7.1*	74.3 ± 9.1	72.3 ± 8.9*
Vo_{2max}, ml · min^{-1} · kg^{-1} (D-2; R0)	46.5 ± 8.1	43.4 ± 6.3*	46.9 ± 5.8	43.1 ± 3.6*

* $P < 0.05$ vs. before (2-way repeated-measures ANOVA followed by Fisher's LSD post hoc test).

location was standardized as follows: The bottom of the probe was seated firmly in contact with the collarbone, the medial side in contact with the trachea (transducer vertical). One automated sweep was performed, then the probe was rotated 90° without moving the location (transducer horizontal), and another sweep performed. From these two sweeps, the long axis and short axis views required for JVvol calculation were extracted. Minimal pressure was applied on the skin by the probe to avoid compressing and changing the JV cross-section.

Middle cerebral vein velocity: The intracranial veins are usually not investigated clinically in adults and are not easy to visualize using transcranial ultrasound with pulsed wave or color Doppler. The strategy used in the current study was to identify the middle cerebral artery (MCA) by placing the phased-array probe at the temple between ear and eye, and then, while maintaining contact with the zygomatic arch, scan the area using color Doppler. The Doppler filter was set to low because of the low venous blood velocities. Conversely, the sample volume was set to large, to facilitate the detection of any venous flow in the vicinity of the MCA. The maximal velocity was measured using manual calipers from the pulsed Doppler vein trace.

Portal vein diameter was measured at the main portal vein trunk using the biliary duct as the definitive landmark differentiating a branch from the trunk. The abdominal probe was located at the intersection of the mammillary and xiphoid lines and oriented with the probe marker at 45° counterclockwise from the right mammilliary line.

Ultrasound measurements (SV, EF, JVvol, MCVv, and PV) were conducted before DI (Pre) in a semirecumbent position as they would be positioned inside the tank and at Day 4 inside the tank: at Day 4 morning (D4 AM) for the no-cuff subjects, and for the cuff subjects prior to donning the cuffs for the day, then at Day 4 evening (D4 PM) after 8 h for the no-cuff subjects and after 8 h with cuffs on for the cuff subjects. An additional JVvol measurement was performed at Day 1 after 2 h spent in the tank (D1-2H) with the cuff on (for the cuff subjects). All study measurements were conducted in a quiet room at a temperature of ~25°C.

Data Analysis

To test the hypothesis that 4 d of DI affected these main outcomes, a 2 × 2 repeated measures ANOVA was used to compare Pre to D4 AM with a main effects analysis for time (Pre and D4 AM) and condition (Control or Cuff), followed by a Shapiro test for normality on the residuals. Significance was set at $P < 0.05$; means are reported as ± SDs. All tests were coded in R 3.6.0 (R Core Team, Netherlands). To test the hypothesis that wearing the cuffs for 8 h during DI affected cardiac function and venous redistribution, a dependent *t*-test was used to compare D4 AM to D4 PM, preceded by a Shapiro test for normality.

RESULTS

On the fourth day of dry immersion, in the morning before donning cuffs if worn (D4 AM), cardiac SV and EF reduced significantly in both groups with no difference between the cuff and control groups (SV: 111 ± 23 cm^3 to 93 ± 24 cm^3, df = 2, $P < 0.003$; EF: 0.66 ± 0.07 to 0.62 ± 0.07 mL, df = 2, $P < 0.026$; **Fig. 1**). At D4 PM, there was no significant difference observed for SV and EF compared to D4 AM.

On Day 1, after 2 h in the tank (DI-2H), the JVvol increased significantly in both groups compared to their Pre values. However, the cuff group showed a smaller increase in JVvol after 2 h compared to the controls (Co: 0.27 ± 0.15 cm^3 to 0.94 ± 0.22 cm^3, $P < 0.01$; CU: 0.32 ± 0.13 cm^3 to 0.64 ± 0.32 cm^3, $P < 0.05$, df = 3; **Fig. 2**).

At D4 AM, JVvol remained significantly higher in both groups compared to Pre (Co: 0.47 ± 0.22 cm^3, CU: 0.35 ± 0.14 cm^3, $P < 0.05$), with no significant thigh cuff effect. Having worn the thigh cuffs for 3 d previously and then measuring on the fourth day prior to donning the cuffs for the day, this result demonstrated that there was no residual or "memory" effect on JVvol. From D4 AM to D4 PM, JVvol was not significantly different (Co: 0.59 ± 0.33 cm^3 to 0.42 ± 0.20 cm^3; CU: 0.38 ± 0.13 cm^3 to 0.30 ± 0.09 cm^3; df = 1, $P > 0.05$).

At D4 AM, the velocity in the MCVv was not significantly different from Pre (Co: 11.5 ± 1.66 to 10.25 ± 2.15 cm · s^{-1}; CU: 10.94 ± 3.93 to 9.56 ± 0.98 cm · s^{-1}, df = 1, $P > 0.05$) and no difference was found between the two groups (**Fig. 3**). From

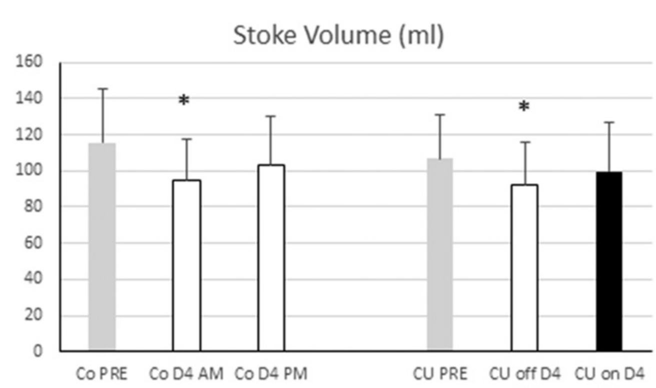

Fig. 1. Stroke volume (SV) measured at Pre-DI, at D4 morning (AM) without cuff for the cuff subjects, and at D4 evening (PM) after 8 h with cuffs on, for the cuff subjects, both in control (Co) and cuffs (CU) subjects (mean ± SD). DI effect in both groups was significant at D4 AM from Pre (*$P < 0.05$).

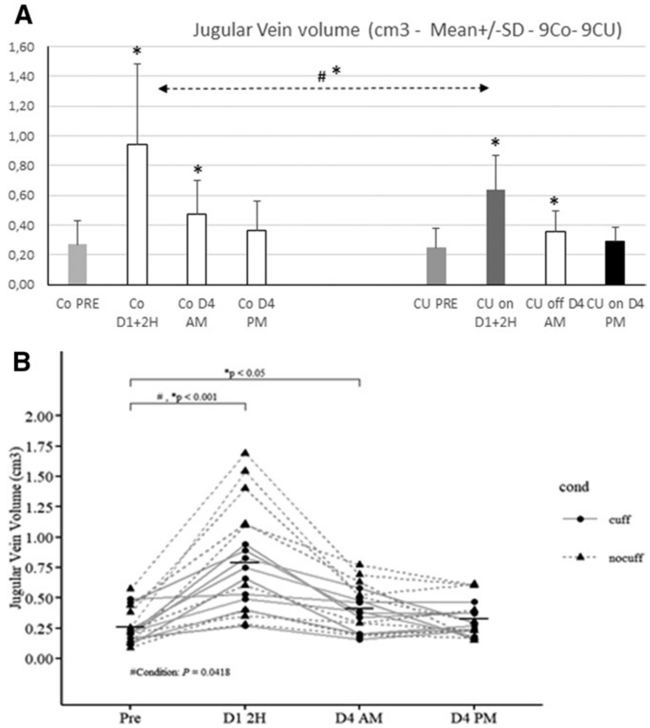

Fig. 2. A) Jugular vein volume (cm^3) measured at Pre-DI, after 2 h (D1 2H) in DI (cuffs on for cuffs group "CU"), at D4 AM (cuffs off for the CU group), and at D4 PM (cuffs on for the CU group) (mean ± SD). B) same data subject by subject. DI effect in both groups was significant at D1 2H and D4 AM from Pre ($^*P < 0.05$). Thigh cuffs effect was significant at D1 2H only ($^{\#*}P < 0.05$).

D4 AM to D4 PM, MCVv did not show any significant change (Co: 10.25 ± 2.15 to 10.20 ± 2.24 cm · s^{-1}; CU: 9.56 ± 0.98 to 10.97 ± 3.35 cm · s^{-1}, $P > 0.05$).

At D4 AM, PV diameter did not show any significant change from Pre, with no thigh cuff effect (Co: 12.5 ± 0.54 mm to 12.4 ± 0.83 mm; CU: 13.0 ± 0.49 mm to 12.7 ± 0.87 mm, $P > 0.05$; **Fig. 4**). From D4 AM to D4 PM, PV diameter did not show any significant change, with no thigh cuff effect (Co: 12.4 ± 0.83 mm to 12.6 ± 0.87 mm; CU: 12.7 ± 0.87 mm to 12.3 ± 0.9 mm, $P > 0.05$).

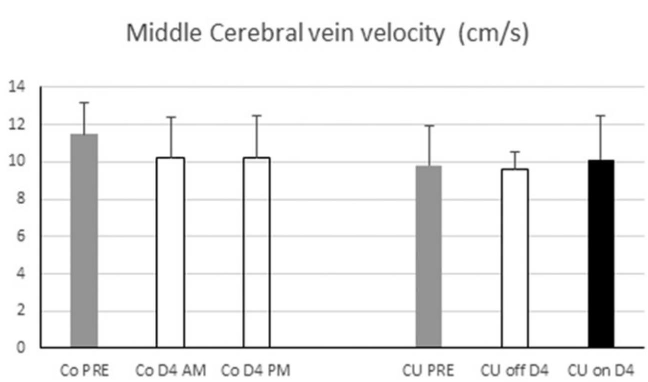

Fig. 3. Middle cerebral vein velocity (MCVv, cm · s^{-1}) measured at Pre-DI, at D4 morning (AM) without cuff for the cuff subjects, and at D4 evening (PM) after 8 h with cuffs on for the cuff subjects, both in control (Co) and cuffs (CU) subjects (mean ± SD).

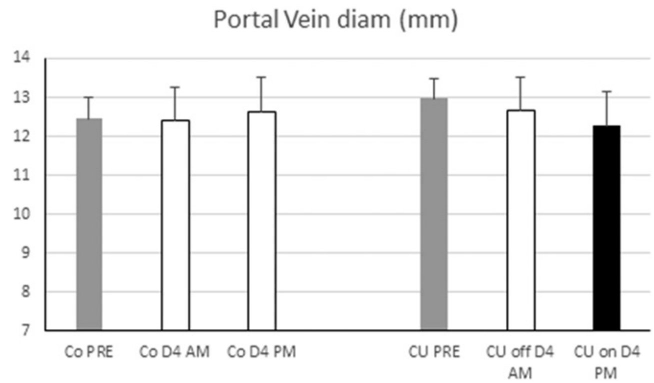

Fig. 4. Portal vein diameter (PV, mm) measured at Pre-DI, at D4 morning (AM) without cuff for the cuff subjects, and at D4 evening (PM) after 8 h with cuffs on for the cuff subjects, both in control (Co) and cuffs (CU) subjects (mean ± SD).

DISCUSSION

Earth-based spaceflight simulation studies have primarily used head-down tilt bedrest as a model of microgravity exposure due, in part, to the tilt angle inducing a fluid shift toward the cephalic and thoracic regions. The use of DI has been proposed as an alternative, more "intense" model of microgravity exposure; however, studies investigating DI-induced fluid shifts and resulting hemodynamic response are limited. After 1 d of DI, a marked reduction in plasma volume (16–30%) has been previously reported,[7] which is similar to what has been observed with spaceflight and head-down tilt bedrest.[3,4] Therefore, the current study investigated fluid redistribution during both the early DI (first 2 h) and late DI (fourth day). A marked shift from feet to head similar to what occurs in spaceflight and head-down bed rest was expected to occur over these 4 d. Surprisingly, however, the present results indicate that an important fluid shift exists mainly during the first hours in DI, and further change becomes moderate/minor by the fourth day.

Cardiac SV decreased significantly during the 4 d in DI, which corresponds well with the decrease in plasma volume measured in the present study.[13] SV and EF did not differ between the two groups; thus the thigh cuffs had no chronic effect on the cardiac volumes, despite being worn for 8 h/d. It is noteworthy that the measurements at D4 AM were performed prior to donning the cuffs for the day; that is, even the cuff group did not wear cuffs at night. Thus, even if the thigh cuff were found to have had an acute effect between morning and evening, these results clearly indicate that any such effect was lost, or "forgotten" overnight. Moreover, the results confirm that there was no significant cardiac volume change after 8 h with the cuffs on (from D4 AM to D4 PM). Thus, we did not observe any "memory" or residual effect of the cuffs on the cardiac parameters after 4 d in DI, nor any acute effect on the cardiac parameters after wearing them all day on the fourth day.

These results appear to be in contrast to previous work. Spaceflight (6 mo duration) and head-down tilt bed rest (60 d duration) studies reported a partial restoration of cardiac volume by the evening (which had decreased) after having worn the thigh cuffs for 8 h during the day.[4,8] DI is a uniquely different model from spaceflight and bed rest due to the following: firstly, the fluid shift disappears quickly during D1 because of the plasma volume loss, and secondly, the DI fluid shift is of less magnitude than in flight or head-down bed rest. This last is because the head-to-foot gravity vector is still present, contrary to microgravity or head-down bedrest, which confounds the fluid shift migration induced by the water pressure applied on the lower limbs, the abdomen, and the chest. Conversely, in flight, similar reductions in plasma volume occur, but the complete loss of the head-to-foot gravity vector strongly exacerbates and maintains the fluid transfer from the trunk/lower body up toward the thoracic/cephalic areas. This sustained and prolonged fluid shift has been confirmed by the constant jugular vein distension measured throughout the mission flight and during head-down tilt bed rest.[3–5]

On Day 1 after 2 h spent in the tank, JVvol increased significantly compared to baseline in both groups, confirming that immersion induced a measureable and important fluid shift from the lower part of the body to the cervical area, causing the internal jugular vein to distend. This is in agreement with a previous 3-d DI study.[1] Nevertheless, JVvol increase observed after 2 h in the tank was of lesser amplitude than during this previous study. The reason could be methodological: 1) the weight of the fabric used to construct the water bags may have been different, which would contribute to different hydrostatic pressure applied to the skin and body; and, similarly, 2) the participants' bodies may not have been submerged equally under the surface of the water.

After 2 h in the tank, JVvol was less distended in those subjects wearing the cuffs, which indicates that the thigh cuffs trapped a significant amount of fluid in the lower limbs. This is in agreement with what was observed in flight and in head-down tilt bed rest when using the same thigh cuff hardware and procedure.[4,8]

Lastly, the DI-induced fluid shift was concomitant with an increase in SV during the early phase of DI, and this is consistent with previous DI studies.[12] But since the SV was found to be reduced after the first day[14] (and in the present study), we did not expect to observe further change in JVvol by the fourth day in either group nor a cuff effect. Nevertheless, after 4 d in the tank, the change was less than after the first 2 h, but remained significantly higher compared to Pre-DI. As expected, there was no cuff effect.

After 4 d in DI there is a chronic DI effect (i.e., the fluid shift) in both groups, but no chronic cuff effect. DI induced a major fluid shift effect after 2 h, with a marked JVvol increase. This fluid shift effect was still present after 4 d, but becomes attenuated, contrary to head-down tilt bedrest and spaceflight with no cuff effect.

Because plasma volume and cardiac stroke volume were reduced on the fourth day compared to the first, and because the head-to-foot gravity vector was still pulling the fluid toward the feet, the quantity of fluid shifted toward the head was likely reduced and we observed that the jugular vein was not as distended on the fourth as on the first day. Consequently, the cuffs had less fluid to "work with," i.e., a lower overall blood volume portion stored in the legs and, therefore, had a lesser impact.

In the present study, there was no increase in MCVv after 4 d in DI and no major increase in JVvol. Conversely, in a previous 3-d DI experiment, MVCv increased during the first 2 h in DI together with the JVvol and an index of intracranial pressure (optoacoustic method) in two-thirds of the subjects.[1] Again at D4, the overall decrease in fluid shift available to be shifted because of plasma volume reduction and G_z vector pushing against fluid transfer are probably responsible for this absence in cerebral venous flow velocity.

PV after 4 d in DI was not found to be higher than Pre-DI while PV was found to be increased on D1 after 2 h in a previous 3-d DI experiment.[1] In spaceflight, the portal veins are larger.[5] The marked reduction in plasma volume and the orientation of the gravity vector may also be responsible for these inconsistent DI results.

In conclusion, the DI model seems to be well suited for quantifying the acute effect of fluids shifting from the lower to the upper part of the body, but is less well suited for studying the chronic effect of fluids shifting over several days, or to test countermeasures. Nevertheless, it must be noted that DI remains a model of physical inactivity because the subjects remain more or less motionless, lying recumbent, in the same position, 24 h/d.

ACKNOWLEDGMENTS

The authors would like to acknowledge the sonographers of UMPS-CERCOM, and Ms. Maryannick Porcher, for her contribution to the data collection. We would also like to thank the CNES, CADMOS, and ESA staff who contributed to the organization of the data collection sessions for the experiment.

Financial Disclosure Statement: The present project was funded by CNES (French Space Agency) and ESA (European Space Agency) grants. No conflicts of interest are declared by the authors.

Authors and affiliations: Philippe Arbeille, M.D., Ph.D.,Daniel Greaves, Ph.D., and Laurent Guillon, M.D., University School of Medicine of Tours, Tours, France; and Stephane Besnard, M.D., Ph.D., UNICAEN, Normandy Université, Caen, France.

REFERENCES

1. Arbeille P, Avan P, Treffel L, Zuj K, Normand H, Denise P. Jugular and portal vein volume, middle cerebral vein velocity, and intra cranial pressure in dry immersion. Aerosp Med Hum Perform. 2017; 88(5):457–462.
2. Arbeille P, Chaput D, Zuj K, Depriester A, Maillet A, et al. Remote echography between a ground control center and the international space station ISS using tele operated Echograph with motorized probe. Ultrasound Med Biol. 2018; 44(11):2406–2412.
3. Arbeille P, Fomina G, Roumy J, Alferova I, Tobal N, Herault S. Adaptation of the left heart, cerebral and femoral arteries, and jugular and femoral veins, during short and long term head-down tilt and spaceflights. Eur J Appl Physiol. 2001; 86(2):157–168.
4. Arbeille P, Herault S, Fomina G, Roumy J, Alferova I, Gharib C. Influences of thigh cuffs on the cardiovascular system during 7-day head-down bed rest. J Appl Physiol (1985). 1999; 87(6):2168–2176.

5. Arbeille P, Provost R, Zuj K, Vincent N. Measurements of jugular, portal, femoral, and calf vein cross-sectional area for the assesment of venous blood redistribution with long duration spaceflight (vessel imaging experiment). Eur J Appl Physiol. 2015; 115(10):2099–2106.
6. De Abreu S, Amirova L, Murphy R, Wallace R, Twomey L, et al. Multi-system deconditioning in 3-day dry immersion without daily raise. Front Physiol. 2017; 8:799.
7. Fomin IO, Orlov VN, Radzevich AE, Leskin GS. Effect of water immersion on indicies of central hemodynamics in subjects older than 45 years. Kosm Biol Aviakosm Med. 1985; 19(3):37–40.
8. Herault S, Fomina G, Alferova I, Kotovskaya A, Poliakov V, Arbeille P. Cardiac, arterial and venous adaptation to weightlessness during 6-month MIR spaceflights with and without thigh cuffs (bracelets). Eur J Appl Physiol. 2000; 81(5):384–390.
9. Kozlovskaya IB, Grigoriev AI, Stepantzov VI. Countermeasure of the negative effects of weightlessness on physical systems in long-term space flights. Acta Astronaut. 1995; 36(8–12):661–668.
10. Macias BR, Liu JH, Grande-Gutierrez N, Hargens AR. Intraocular and intracranial pressure during head-down tilt with lower body negative pressure. Aerosp Med Hum Perform. 2015; 86(1):3–7.
11. Miki K, Klocke MR, Hong SK, Krasney JA. Interstitial and intravascular pressure in conscious dogs during head-out water immersion. Am J Physiol. 1989; 257(2, Pt. 2):R358–R364.
12. Navasiolava NM, Custaud M-A, Tomilovskaya ES, Larina IM, Mano T, et al. Long-term dry immersion: review and prospect. Eur J Appl Physiol. 2011; 111(7):1235–1260.
13. Robin A, Auvinet A, Degryse B, Murphy R, Bareille MP, et al. DI-5-Cuffs: Venoconstrictive Thigh Cuffs Limit Body Fluid Changes But Not Orthostatic Intolerance Induced by a 5-Day Dry Immersion. nFront Physiol. 2020; 11:383.
14. Shulzhenko EB, Tigranyan RA, Panfilov VE, Bzhalava II. Physiological reactions during acute adaptation to reduced gravity. Life Sci Space Res. 1980; 18:175–179.
15. Shulzhenko EB, Vil-Vilyams IF. [The possibility to maintain a long term water immersion by using the method of "dry immersion"]. Kosm Biol Aviakosm Med. 1976; 10:82–84 [in Russian].
16. Teichholz LE, Cohen MV, Sonnenblick EH, Gorlin R. Study of left ventricular geometry and function by beta scan ultrasonography in patients with and without asynergy. N Engl J Med. 1974; 291(23):1220–1226.