ORIGINAL ARTICLE

Effect of graded water immersion on vital capacity and plasma volume in patients with cervical spinal cord injury

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Study design: A case–control study was conducted.

Objective: The aim of the study was to test the hypothesis that the increase in hydrostatic pressure on the abdominal wall may be the major determinant of vital capacity (VC) improvement in tetraplegic subjects during water immersion, despite the blood volume shifts from the legs and abdomen to the thorax.

Setting: The study was carried out in the Rehabilitation Center, Brasília/DF, Brazil.

Methods: In total, 11 men with tetraplegia (complete motor lesion, C4–7, 30.4 years old) and 12 healthy controls were studied. Hematocrit level and spirometry values were obtained on dry land and at each level of immersion (the pelvis, xiphoid and neck).

Results: Baseline spirometry value of tetraplegic subjects showed reduced VC ($53.3 \pm 17.4\%$ of predicted), whereas all control subjects had $>80\%$ of predicted values. Neither group showed significant changes in VC at the pelvic and xiphoid levels of immersion. In tetraplegic subjects, VC increased by 27.2% at the neck level (± 25.8 , $P < 0.008$), whereas in healthy subjects it decreased by 6.3% (± 5.0 , $P < 0.008$). Both groups showed significantly increased inspiratory capacity only when immersed to the neck. Hematocrit level of tetraplegic subjects fell significantly with immersion to the xiphoid and neck levels ($P < 0.017$), which occurred in controls only at the xiphoid level ($P < 0.017$).

Conclusions: Hydrostatic compression may be the main contributor to improving VC in tetraplegic subjects immersed in water. This improvement occurs despite increased plasma volume during immersion. *Spinal Cord* (2010) 48, 375–379; doi:10.1038/sc.2009.139; published online 27 October 2009

Keywords: immersion; spirometry; quadriplegia; hematocrit; hydrostatic pressure; water

Introduction

Immersion at the neck level reduces vital capacity (VC) in healthy individuals.¹ This reduction has been primarily attributed to the restrictive effect of increased central blood volume.^{1,2} Paradoxically, an increase in VC has been observed in immersed tetraplegic individuals.^{3,4} Another study showed that cardiac output increases in tetraplegic subjects during head-out immersion, but it did not investigate the effect on pulmonary function.⁵

These observations may point to common ‘out-of-water’ clinical conditions in these patients. VC increased in tetraplegic subjects when they shifted from seated to the supine posture.⁶ This postural dependence was related to changes in residual volume and diaphragm position, and was not a factor when the abdomen was tightly

supported by elastic straps.⁶ Blood shift between the lower extremities and the thorax had little effect, as was shown by inflating cuffs fitted around the base of the patients’ legs before they being shifted to the supine posture.⁶

It has not been determined whether immersion effects share the same mechanisms of postural change and abdominal binding. Pulmonary and hemodynamic changes in tetraplegic subjects during head-out immersion in water have yet not been compared with healthy controls under equal experimental conditions. The purpose of this study was to review the fragmented data from the literature and to show that VC improvement among tetraplegic patients is related to hydrostatic pressure, despite increases in central blood volume. Therefore, tetraplegic and control subjects were studied during graded immersion by VC and hematocrit level determinations. In addition, to complete the investigation, we also studied subjects with and without cuffs at the base of the legs, inflated before and deflated during immersion.

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Materials and methods

Participants

In total, 11 male patients with spinal cord injury (SCI) and 12 healthy male volunteers were recruited between February 2003 and March 2004. Tetraplegic patients had complete motor lesions (C4–C7; American Spinal Injury Association (ASIA) A/B)⁷ (Table 1). The volunteers had a mean age of 27 years (range 22–38) and were orthopedic patients or physiotherapists from the SARA Network of Rehabilitation Hospitals.

The study was conducted at the SARA Network Hospital in Brasília-DF, Brazil. All the patients with SCI in this study were participants in the Network's rehabilitation program. Subjects with clinical instability, history of tracheostomy, active respiratory disorder, or conditions that prevented them from partaking of water activities (for example, skin infection and incontinence) were not considered for inclusion in this study.

Procedures

The procedures were conducted in the afternoon, at 2–3 h after the patient had eaten a light lunch, at the Hydrotherapy Department of the SARA/Brasília Hospital, a closed environment with ambient temperature varying from 27 to 30 °C. Before starting, all participants drank 400 ml of water. A heparin lock (In Stopper LL, B Braun Melsungen, Germany) venous access catheter (Jelco no. 20, Johnson & Johnson, New Brunswick, NJ, USA), inserted in the forearm or hand, was used throughout the procedures. Initially, participants underwent slow and forced spirometry (MasterScope, Erich Jaeger GmbH, Germany) at the poolside. Spirometry procedures conformed to the recommendations and predictive equations of the ATS,^{8,9} modified for use in patients with SCI.¹⁰ The best of three reproducible values was considered. After these procedures, 2 ml of blood was drawn.

The measurements of slow spirometry and hematocrit level were repeated during immersion in thermoneutral water (33.5–34.5 °C) with the subject at three successive levels of depth: the anterior superior iliac spine, xiphoid and sternal notch (hereafter called the pelvis, xiphoid and neck, respectively). All measurements were obtained in a seated

upright position at each level of immersion. Each subject spent a minimum of 5 min at each level in order to achieve a steady hemodynamic state before submitting spirometry values and blood samples. The arm with the venous access remained above water during the entire process of evaluation, whereas the other arm was kept at the subject's side. All blood samples were collected and stored in a vacuum tube (BD Vacutainer Systems, Franklin Lakes, NJ, USA), which contained EDTA. Hematocrit level was measured (T890, Coulter Corporation, Miami, FL, USA) at the end of each procedure. All subjects seated on a chair were lowered into the pool using an electromechanical crane.

Two subjects with complete cervical motor injury, aged 27 (C8 level) and 17 (C5) years, along with two control subjects, 27 and 31 years old, were also studied. All the four additional subjects were male. The same procedure was followed to measure VC in four successive stages. All measurements were taken with the subjects seated and with bilateral electronically controlled and synchronized pressure cuffs (Zimmer Surgical Medical, Warsaw, IN, USA, ATS 2000) fitted around each leg at the groin. The sequence was the same for each subject beginning with the basal measurement out of the water, with the cuffs deflated. The second measurement out of the water was taken 5 min after simultaneous cuff inflation to diastolic pressure plus one-half of the pulse pressure (systolic minus diastolic pressure). Subjects were lowered into thermoneutral water with the cuffs still inflated. After 5 min of immersion, VC was again measured. The cuffs were then deflated. After 5 min, VC was measured again when the subjects were still immersed in water.

Statistical analysis

All variables presented normal distribution (Shapiro-Wilk test). Analysis of variance (ANOVA) for repeated measurements was used to compare the effects of different levels of immersion between and within groups (P -value <0.05 was considered statistically significant). Within each group, the results at different levels were analyzed by the paired sample t -test. As per the Bonferroni correction, a P -value <0.008 was considered statistically significant for spirometry parameters,

Table 1 Patients' characteristics and profile

Patient no.	Age (years)	Time since injury (months)	Injury level/ASIA	Smoking status
1	26	2	C5-C6/B	Current
2	33	8	C6/B	Never
3	39	12	C5-C6/B	Never
4	40	8	C5-C7/B	Never
5	34	9	C6/A	Never
6	31	11	C4-C5/A	Current
7	32	15	C5-C6/A	Never
8	28	3	C6-C7/B	Never
9	26	4	C5-C6/B	Never
10	23	5	C7/A	Never
11	22	6	C4/A	Never
Mean	30.4	7.6	—	—
± s.d.	6.0	3.8	—	—

Abbreviation: ASIA, American Spinal Injury Association.⁷

A denotes complete motor and sensory loss and B denotes incomplete injury, only sensory is preserved at S4–S5.

and P -value <0.017 for hematocrit level. The results were expressed as absolute values, as percentage predicted for the spirometry standard and as percentage change ($\Delta\%$) between basal and each level of immersion. Pearson's correlation coefficient was used to assess VC relationship between percentage change with head-out immersion and basal percentage predicted in tetraplegic patients. StatView for Windows (SAS Institute Inc., Campus Drive Cary, NC, USA, version 5.0.1) was used for all statistical analyses.

We certify that all applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during the course of this research.

Results

The average for all percentage predicted values of the tetraplegic participants was lower than that of the control group ($P<0.05$) at baseline; the only exception was the ratio of forced expiratory volume in 1 s to forced VC. The tetraplegic group exhibited a moderate restrictive ventilatory impairment, characterized by an average VC of $53.3 \pm 17.4\%$ of predicted (range 25.5–77.4%), whereas participants from the control group were all within the predicted range ($>80\%$). The expiratory reserve volume was the most affected component of VC in the tetraplegic group ($39.8 \pm 21.4\%$ of predicted) (Table 2).

The ANOVA for repeated VC showed an interaction between the groups and the levels of immersion ($P<0.001$). Within each group, the VC differed in relation to the level of immersion ($P<0.005$). During immersion, the mean VC percentage change from the basal values varied between groups. At the pelvic level, it was reduced in tetraplegic and control subjects: $-6.8 \pm 12.5\%$ and $-1.9 \pm 5.7\%$, respectively, with no differences between or within groups. At the xiphoid level, the tetraplegic group showed an increase in VC ($8.6 \pm 26.2\%$), whereas the control group continued to exhibit a decline ($-4.3 \pm 5.5\%$), but with no differences between or within groups. At the neck level, the groups confirmed the previous tendency and showed divergent behavior ($P<0.001$). In controls, the decrease in VC was maintained ($-6.3 \pm 5.0\%$, $P<0.008$), whereas an increase in VC ($27.2 \pm 25.8\%$, $P<0.008$) was observed in tetraplegic patients (Figures 1 and 2). Only one tetraplegic patient (#10) exhibited a decrease of -3.7% in VC at the last immersion level, without complaints of breathlessness. In the tetraplegic group, we observed a strong negative correlation between the improvement of percentage

change in VC at the neck level of immersion and the respective basal impairment (% predicted) ($r = -0.868$; 95% confidence interval: -0.965 to -0.560).

Figure 1 Values of vital capacity measured in immersed (neck) and dry (land) environments both in seated postures in 11 tetraplegic patients (closed circles) and 12 healthy control subjects (open circles). The continuous diagonal line is the line of identity.

Figure 2 The baseline and post-immersion level means ($\pm$ s.d.) of slow vital capacity (VC), inspiratory capacity (IC) and expiratory reserve volume (ERV), for control and tetraplegic groups. Intragroup analysis: * $P<0.008$ versus baseline; $^{\dagger}P<0.008$ versus pelvis; $^{\S}P<0.008$ versus xiphoid.

Table 2 Baseline mean values of slow and forced spirometry parameters (percentage predict) of tetraplegic and control groups^a

	VC, l (%pred)	IC, l (%pred)	ERV, l (%pred)	FVC, l (%pred)	FEV1, l (%pred)	FEV1/FVC, $\times 100$
Tetraplegic group, $n=11$						
Mean	2.80 (53.3)	2.32 (62.4)	0.61 (39.8)	2.70 (51.4)	2.44 (55.8)	109.39
$\pm$ s.d.	0.94 (17.4)	0.66 (16.3)	0.31 (21.4)	0.92 (17.4)	0.80 (17.7)	6.51
Control group, $n=12$						
Mean	5.20 (101.3)	3.74 (104.7)	1.46 (94.8)	5.05 (99.1)	4.31 (100.4)	101.06
$\pm$ s.d.	0.74 (11.2)	0.80 (19.6)	0.55 (36.1)	0.69 (10.9)	0.59 (11.5)	7.63

Abbreviations: ERV, expiratory reserve volume; FEV1, forced expiratory volume 1 s; FVC, forced vital capacity; IC, inspiratory capacity; VC, slow vital capacity.

^aAll means of percentage predicted values were different between the groups ($P<0.05$).

Figure 3 Vital capacity (VC) percentage change from basal (air basal) in three successive experimental conditions: ambient air with cuffs inflated to mean arterial pressure (air cuff on); immersion at neck level with cuffs inflated (water cuff on); immersion with the cuffs deflated (water cuff off). The amount of decrease in VC after water cuff off in controls A and B was 140 ml (−2.5%) and 200 ml (−3.4%), respectively. *SCI-A, 27 years, American Spinal Injury Association (ASIA) A, 6 years after firearm injury, motor level at C8. Baseline VC of 3.6 l (67% predicted). The amount of decrease in VC after water cuff off was 310 ml (−7.5%). †SCI-B, 17 years, ASIA A, 2.5 years after diving injury, motor level at C5. Baseline VC of 1.2 l (28% predicted). The amount of decrease in VC after water cuff off was 100 ml (−5.8%).

During graded immersion, we noted a progressive increase of inspiratory capacity. It became significant at the xiphoid level for the control group ($P < 0.008$) and at neck level for both groups ($P < 0.008$). This improvement was greater in the tetraplegic ($36.1 \pm 23.14\%$) than in the control group ($15.7 \pm 15.6\%$) ($P < 0.05$) (Figure 2). The expiratory reserve volume diminished progressively at each level of immersion, attaining significance at the xiphoid level for the control group ($-27.6 \pm 21.9\%$, $P < 0.008$), and for both groups at the neck level ($-56.4 \pm 16.3\%$, $P < 0.008$, controls; $-40.3 \pm 51.5\%$, $P < 0.008$, tetraplegics) (Figure 2).

There was a mean decrease of 4% in hematocrit levels in each group (ANOVA, $P < 0.01$). Hematocrit levels fell significantly at xiphoid and neck levels ($P < 0.017$) in tetraplegic subjects, whereas in the control group, hematocrit levels fell significantly only at the xiphoid level ($P < 0.017$).

In the complementary study, there was no change in VC with out-of-water inflation of cuffs (Figure 3). During immersion with the cuffs inflated, both tetraplegic patients showed a VC improvement of 14% (C8 level) and 47% (C5). Under the same conditions, the control subjects had changes within $\pm 1\%$. After deflation of the cuffs during immersion, all four subjects showed a decline in VC.

Discussion

Patients with tetraplegia exhibit a gradual improvement in VC reaching a 27% increase at the neck level when immersed at progressively deeper levels in water. This improvement comes as a result of an increased inspiratory reserve capacity, but with a reduction in expiratory reserve volume. In contrast, the control group shows an average reduction in VC of 6% at the neck level. These changes occur despite an increase in volemia. The increased VC of the patients may be mainly related to a reduction in residual volume.

Previously, four publications have addressed pulmonary function and head-out immersion in subjects with SCI.^{3,4,11,12} Their findings showed an increase of 25% in VC, whereas their control groups decreased by 5%.^{3,11} Their findings also showed a decrease of 49 percentage points in predicted values of residual volume, whereas their control groups decreased by 6 percentage points.^{11,12} Total lung capacity decreased by 8% from land to immersion in tetraplegic subjects.³ Water temperature and time of immersion, parameters of considerable physiological importance, differed among these studies.

Evidence suggests that the ideal water temperature for such experiments is 33–35 °C.¹³ Within this thermoneutral temperature range, effects on body core temperature and pulmonary volumes are minimized. Furthermore, individuals with SCI are partially poikilothermic, in which their core temperature tends to follow changes in ambient temperature.¹⁴ This study investigated pulmonary volumes at different levels of immersion, ensuring to minimize potential confounding effects of time of immersion and water temperature. Two other components were also added, namely progressive deepening of immersion and an estimate of plasma volume change.

The pelvis, xiphoid and neck levels are used as reference levels for assessment of the cardiovascular effects of immersion, thereby gauging the contribution of displaced plasma volume from the lower limbs, abdomen and thorax to the central circulation.¹³ The shift of volume has been estimated at 700 ml to the chest during immersion in healthy individuals.^{1,2} This increase includes both blood and mobilized interstitial fluid to the central blood volume,¹⁵ which can be estimated by hematocrit change.¹⁶ Xiphoid and neck references are also useful in discriminating the effects of abdominal hydrostatic compression from thoracoabdominal hydrostatic compression on pulmonary volumes.¹³

We found a significant hematocrit level decline in both groups, compatible with the increased central blood volume.¹⁶ Individuals with tetraplegia had an increase in cardiac output of the same magnitude compared with control subjects during immersion.⁵ With immersion to the pelvic level, we found a small reduction in VC in both groups. This may suggest that the hemodynamic effects on VC restriction are noticed even at this level. However, with increased depth of immersion, the tetraplegic group showed an increase in VC, whereas control subjects had the apparently opposite, even though the hematocrit level fell equally in both. In control subjects, there is a reduction in VC of 3–10% and residual volume of 9–16% after water immersion.^{2,17} Intrathoracic blood pooling has been suggested as the main cause of the decrease in VC and pulmonary compliance, as well as the increase in occlusion volume and work of breathing.¹⁷

In general, on land, the VC of individuals with a high spinal cord lesion is reduced by one-third of the predicted value.¹⁸ Lesions that preserve phrenic nerve function, below C5, are characterized by expiratory abdominal musculature flaccidity. This permits a descent of the diaphragm apex, reducing its area of apposition with the chest wall, leading to mechanical inefficiency.¹⁸ The pulmonary function during immersion may have similar observations during postural

changes and abdominal compression in dry conditions. Simply changing from seated to the supine position has been shown to improve the VC and inspiratory capacity by 30–60% in tetraplegic individuals.⁶ A similar improvement from 10 to 30% is found when abdominal girdles are added to a seated position.¹⁹ These maneuvers may improve diaphragmatic excursion by pushing the apex of the diaphragm cephalad, decreasing its radius, with more effective transdiaphragmatic pressure (Laplace's law).

Hydrostatic pressure during immersion at the xiphoid level seems to evoke the same mechanisms of abdominal musculature support and cephalic transposition of the diaphragm apex as described for the lying position and abdominal binder. However, Estenne and De Troyer⁶ showed that tetraplegic subjects during postural change and abdominal binder had increased VC while decreasing residual volume, without significant changes in the total lung capacity. Jaeger-Denavit *et al.*³ and Bosch and Wells¹¹ achieved the same results with head-out immersion. These facts are against our previous hypothesis of VC increases related to better diaphragm efficiency, and support the idea that this improvement has more to do with residual volume reduction. However, observing Figure 2, it seems that the VC improvement continued to increase at the next level, neck, while hematocrit levels continued to decrease. The fact that the addition of thoracoabdominal hydrostatic compression permits further improvement, despite the hemodynamic consequences of immersion, suggests that immersion may involve other mechanisms that are as-yet undefined.

A limitation of this study was the absence of more detailed data on the behavior of all pulmonary volumes. Thus, it is difficult to have a complete vision of graded immersion effects without knowing the total lung capacity and residual volume. These results, although incomplete, do add new knowledge on the balance between pulmonary engorgement with blood and the VC changes during immersion. Another point to be considered was the use of the hematocrit as a surrogate of volemia. This parameter underestimated the real volemia changes.²⁰ However, our aim was only to use it as a marker of changes in both groups, confirming the findings of Tajima *et al.*,⁵ and the changes observed during the release of the cuffs.

Respiratory complications remain the principal factor contributing to morbidity and mortality in patients with SCI.¹⁸ From a clinical perspective, the effects of immersion are important because many of these subjects undergo pool-based therapy. The improvement seen during immersion may translate into possible functional benefits to patients who engage in regular sessions of aquatic activities during treatment or pulmonary rehabilitation, and may help prevent complications. Only prospective and controlled trials can help shed further light on this issue. In conclusion, the thoracoabdominal compression exercised by hydrostatic pressure is the main factor contributing to the improvement in VC of tetraplegic individuals, despite the negative influence of the increase in central blood volume during immersion.

Conflict of interest

The authors declare no conflict of interest.

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