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Fluid Loss under Pressure – Inter- and Intraindividual Variability and Relation to Diving Parameters in SCUBA Divers

Flüssigkeitsverlust unter Druck – inter- und intraindividuelle Variabilität und Abhängigkeit von Tauchparametern bei Sporttauchern

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Summary

- **Introduction:** Sufficient hydration of a SCUBA diver is important to reduce the risk of decompression sickness. Mechanisms of fluid loss in diving and immersion are known, but not quantified. We aimed at relating dive profiles and individual parameters to fluid loss in order to develop an estimation of necessary amount of fluid restoration between dives.
- **Methods:** 41 SCUBA divers with a broad spectrum of ages, sex, and bio data performed 342 single and repetitive dives on air in an open breathing system. Before and after the dives, body weight, bio data and dive profiles were recorded.
- **Results:** Average dive profile was 22.9 meters and 46.5 minutes, average weight loss was 0.8 kg after repetitive dives and 1.0 kg (1.2% relative body weight) after the first dive of the day. Significant correlations were found between relative weight loss and a single dive (no repetitive diving), younger age, dive time, non smoking, body weight and lean body mass. No significant correlation was found for air consumption, fluid intake, circulatory parameters, bio data, water temperature, and salinity.
- **Discussion:** Immersion-induced individual physiological responses are the major mechanisms leading to fluid loss in divers, since correlation with dive and biometric parameters is low. Except for small contribution from humidification of dry breathing gas, dive parameters are not suitable to determine necessary fluid replacement. Only a rough estimate of 1 liter per standard sports dive is possible.

Zusammenfassung

- **Hintergrund:** Sporttaucher müssen auf ausreichend Flüssigkeitszufuhr vor und nach einem Tauchgang achten, um das Löslichkeitsvolumen von Inertgas nicht zu beeinträchtigen und somit das Risiko eines Dekompressionsunfalls nicht zusätzlich zu erhöhen. Mit dieser Untersuchung soll der Einfluss von verschiedenen, vom Sporttaucher leicht messbaren Tauch- und individuellen Parametern auf den zu erwartenden Flüssigkeitsverlust bestimmt werden.
- **Methoden:** 41 Sporttaucher mit breiter Streuung biometrischer Daten absolvierten 342 einzelne bzw. Wiederholungstauchgänge mit Pressluftatemgerät im offenen System. Vor und nach jedem Tauchgang wurden blasenentleertes Netto-Körpergewicht, biometrische und Aktivitätsdaten wie auch die Tauchprofile registriert.
- **Ergebnisse:** Die Tauchgänge hatten eine durchschnittliche Tiefe von 22,9 Metern und eine Dauer von 46,5 Minuten. Dabei trat ein durchschnittlicher Gewichtsverlust bei Ersttauchgängen von 1 Kilogramm (1,2% relatives Körpergewicht) und bei Wiederholungstauchgängen von 0,8 Kilogramm auf. Signifikante positive Korrelationen fanden sich insbesondere bei Nicht-Wiederholungstauchgängen zwischen relativem Gewichtsverlust und jüngerem Alter, Tauchzeit, Nicht-Rauchen, Gesamtkörpergewicht und fettfreier Körpermasse. Kein Zusammenhang fand sich zwischen Gewichtsverlust und Luftverbrauch, vorangehender Trinkmenge, Kreislaufparametern, weiteren biometrischen Daten, Wassertemperatur und Salzgehalt des Wassers.
- **Diskussion:** Da der Zusammenhang des tauchbedingten Flüssigkeitsverlustes mit tauchgangsspezifischen und individuellen biometrischen Daten gering ist, muss dieser auf eine immersionsbedingte Auslösung bekannter physiologischer Reaktionen zurückzuführen sein. Über den geringen Anteil der Atemgasanfeuchtung hinaus lässt sich der Flüssigkeitsverlust anhand von messbaren Parametern nicht vorhersagen, obwohl dieser alters- und tauchzeitabhängig ist. Lediglich eine grobe Schätzung von 1 Liter pro Standard-Sporttauchgang kann erfolgen.

KEY WORDS:
Inert Gas Solution, Dehydration, Decompression, Immersion

SCHLÜSSELWÖRTER:
Inertgas-Löslichkeit, Dehydratation, Dekompression, Immersion

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Introduction

Fluid loss in Self Contained Underwater Breathing Apparatus (SCUBA) divers is well known (8) and dehydration is a major risk factor of decompression sickness (11) due to diminished solution capacity of body fluids for inert gases after pressure reduction caused by ascending from depth. Vice versa, prehydration before a dive reduces the decompression stress as amount of detectable inert gas bubbles in Doppler examinations after the dive (3). Known effects causing dehydration while diving are:

1. Immersion with increased hydrostatic pressure and thus atrial natriuretic peptide secretion (6, 4, 10) due to atrial stretch causing reflex autonomic responses (8) with increased diuresis and electrolyte loss (7) and counter-regulation with increased aquaporin-2 excretion with time (12);

2. Vasoconstriction due to higher thermal conductivity of water against air and as a centralization reaction with increased noradrenaline and vasopressin secretion (1, 4, 6);
3. Sweating due to swimming / exertion with heavy equipment (2, 5) as well as;
4. Humidification of technically dried breathing gas.

Taking into account these mechanisms, also other diving-related conditions such as total air consumption, fluid intake, circulatory parameters, chronic diseases, water temperature and salinity, bio data and preexisting dehydration due to sports and alcohol induced diuresis might contribute to fluid loss in divers.

So far, it is unknown, whether individual and diving related factors contribute to fluid loss in SCUBA diving in a relevant and predictable way and whether the knowledge of easily accessible individual and/or diving related factors could help to estimate fluid loss in Sports SCUBA diving and thus, potentially reduce the risk of diving accidents through adequate hydration. Therefore we aimed on estimating the fluid loss in SCUBA diving in relation to dive and individual parameters. To our knowledge, there is no study that quantifies fluid loss in sports diving and relates it to dive parameters in a larger number of SCUBA dives.

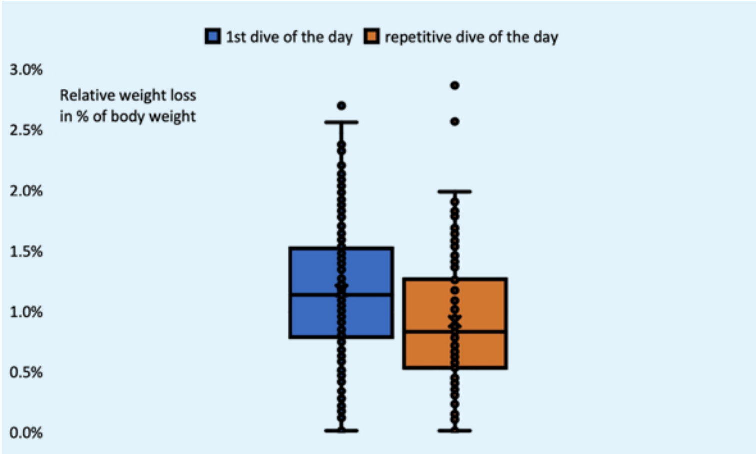

Figure 1

Difference of relative weight losses during the first and any repetitive dive of the same day. Since the data is not distributed normally (Shapiro-Wilk tests, Bonferroni-corrected alpha=5%/n), the one-sided Wilcoxon rank-sum test with continuity correction (Mann–Whitney U test) was applied (p=0.0001). Absolute average weight loss of the first dive was 1.0 kg and of a repetitive dive 0.8 kg only. Dive profiles (time and max. surrounding pressure) did not differ significantly between first and repetitive dives.

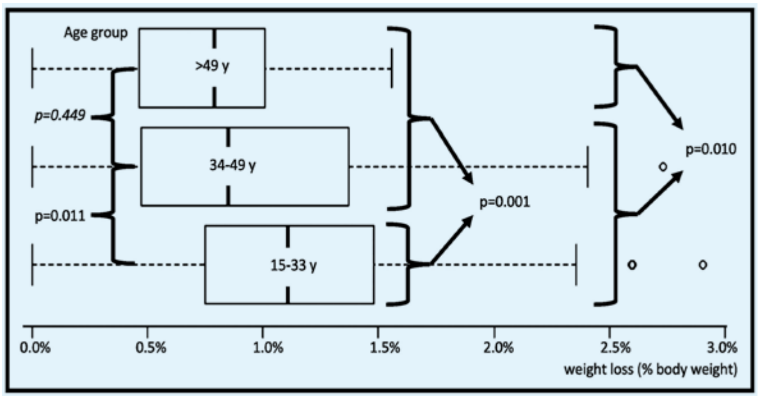

Figure 2

Relative weight loss (% body weight) during a single dive depending on age: Older divers (>49 years) lost less weight compared to younger divers (<34 years). Middle aged divers (34-49 years) showed a broad spectrum of relative weight loss.

Methods

After informed consent and ethical approval, 41 SCUBA divers of mixed sexes and ages were weighed before and after a total of 342 dives on compressed air in order to include intra- and interindividual effects. Castagna et al. (2) found a weight loss of 0.99 kg in 12 warm water fin-swimming combat divers compared to 0.72 kg in resting water immersion in highly standardized 2 dives per diver (p=0.003). Taking into account sports SCUBA divers variability in age, gender, water temperature and dive parameters, we roughly aimed on 4 groups and 8 dives per diver to accomplish for the expected variability of sports SCUBA dives at a 95% confidence interval.

The diving profiles themselves were not influenced by our study. Urine was considered as relevant diving-induced fluid loss and therefore was discharged before weight was taken after the dive and – for correct recording of dive related weight loss through urine output – also before the dive. The study protocol was as follows:

1. Diver (undressed, empty bladder) presents before the intended SCUBA dive
2. Recording of body weight, vital signs, bio, impedance and individual behavioral data
3. Gear-up, SCUBA-dive
4. Diver (undressed, empty bladder) presents after the SCUBA dive
5. Recording of body weight, vital signs, impedance data, technical and individual details of the dive
6. Food & drinks allowed & recorded

No fluid or solid intake and solid discharge was allowed between the measurements before and after the dive.

The same electronic scale (Beurer BF 105 diagnostic) was calibrated before each measurement and equipped with electrodes for all 4 extremities for estimation of body water, muscle and fat content via impedance recordings. Due to limited reliability of impedance recordings especially in wet environment and expected vasoconstriction, these data were considered as additional information and not a critical part of our investigation. Medical history was taken for each diver including height, amount of smoking and chronic diseases. Before and after each dive, diving parameters like depth, dive time, water temperature, salinity, air consumption, surface interval, subjective stress during the dive, freezing and general activity level in 5 categories (1=no physical activity, 5=daily intensive physical activity more than one hour) were recorded, as well as previous cumulated fluid intake during surface interval and alcohol intake the night before, and vital signs (blood pressure, heart rate). Data recording and management was done with Microsoft Excel, Statistics with RStudio. Subgroups were analyzed for the first dive of any day (surface interval more than 12 hours) and repetitive dives (the same day, surface interval below 12 hours) in order to account for usual desaturation times in non-decompression sports diving on air.

Multiple testing was observed for data analysis and data was tested for normal distribution (using Shapiro-Wilk-Test, Bonferroni-corrected alpha=5%/n) and if so, ANOVA-Tests, otherwise Kruskal-Wallis tests were applied; two samples ›

Table 1

Significant rank correlation between relative weight loss (% of body weight) during the first dive of the day (otherwise specified as repetitive dive) and other parameters. For decompression safety, a higher surrounding pressure is related with a longer dive time, but not the other way around.

Y(I)/X	RELATIVE WEIGHT LOSS (% DIFFERENCE BEFORE – AFTER DIVE)	CORRELATION R	P
1	Dive group: no repetitive diving the same day	0.224	0.0001
2	Surface interval before any repetitive dive (hours)	0.223	0.0265
3	Age group (per 10 years)	-0.209	0.0028
4	BMI (body mass index kg/m2)	-0.194	0.0057
5	Dive time (minutes)	0.152	0.0338
6	Smoking (1: >1 packyear, 2: <1 packyear, 3: non-smoking)	0.111	0.0495
7	Body muscle (%)	0.128	0.0248
8	Body water (%)	0.149	0.0344
9	Max. surrounding pressure during the dive (bar)	0.114	0.0459

t-test for normally distributed data, otherwise pairwise Wilcoxon-rank-sum tests with continuity correction (Mann–Whitney U tests) for post-hoc analysis were applied.

Results

All divers used compressed air as breathing gas and all dives were within sports diving limits of 3-43 meters (average 22.9 meters) and a duration of 30-120 minutes (average 46.5 minutes). On ascent, one safety stop was standard procedure and max. one decompression stop was required by the diving computer and strictly observed. No decompression accident or other severe complications occurred. 311 dives with full data set were included in the post-dive analysis. Weight loss during these dives varied between 0 and 2.9 kg per dive, with an average of 0.9 kg per dive. Consumption of dry air was 150-2850 bar*liters per dive (average 1800 bar*l).

Most weight was lost during the first dive of the day. Repetitive dives caused a diminished absolute and relative weight loss, irrespective of dive profile (Figure 1):

The relation between the relative weight loss (% of body weight) during a dive and each of the recorded parameters such as body constitution, age, smoking, diving parameters (depth, surrounding pressure) and dive time is represented in Table 1. These parameters are not normally distributed (Shapiro-Wilk test, Bonferroni-corrected alpha=5%/n); therefore, the Spearman rank correlation is applied and given together with corresponding p-values in relation to zero-correlation (zero-hypothesis):

Age distribution was between 15 and 69 years with an average age of 30 years. In a detailed analysis of the relationship between weight loss and age, the following age groups were found that differed significantly in weight loss during a dive (Figure 2). Since the data is not distributed normally (Shapiro-Wilk test for Bonferroni-corrected alpha=5%/n), the Kruskal-Wallis test was applied to compare these age groups (zero-hypothesis: expected value of weight loss in all age groups is the same, p=0.004). For post-hoc analysis, two-sided Wilcoxon rank-sum tests with continuity correction (Mann–Whitney U tests) were applied pairwise and displayed with p-values:

The relation between relative weight loss (% body weight) during the first dive and the corresponding dive time is displayed in Figure 3:

The variability of weight losses during a dive is both inter- and intraindividual. The data is distributed normally (Shapiro-Wilk tests, Bonferroni-corrected alpha=5%/n) and without significant differences of variance (Bartlett-Test, p=0.9381). Upon application of the ANOVA test, group differences were revealed (p=0.0238). Therefore, two-sample t-test (alternative hypothesis="less") was applied for post-hoc analysis with p-values displayed in Figure 3. It shows that dives with a dive time more than 54 minutes caused a significantly higher relative weight loss compared to dives of less than 35 minutes duration. The relative weight loss comparison of other groups did not reach significance.

No significant correlation between relative weight loss and observed parameters was found for total air consumption (p=0.185), cumulated daily fluid intake before the dive (p=0.187), circulatory parameters (blood pressure, heart rate and their changes before and after the dive; p=0.125-0.787), chronic diseases (p=0.499), stress (p=0.425), alcohol intake the day before (p=0.183), freezing during the dive (p=0.092), body height (p=0.457), sex (p=0.442), intensity of sports the day before (p=0.624) and general activity (p=0.871), water temperature and water salinity (p=0.498).

Taking into account that total air consumption is related to dive time and depth, the relationships of air consumption in liter/minute and liter/minute*bar were tested as well. However, neither correlation nor significance level revealed any relation to relative weight loss.

Discussion

Our results revealed a higher fluid loss in longer and deeper dives and also in the first dive compared to repetitive diving during a day. Further, we found significant influence of non-smoking, younger age and lean body mass on fluid loss.

From individual parameters, very interesting findings were, that non-smokers and those of a high lean body mass seem to lose more fluid (relative weight loss) during a dive compared to others. The individual effect of age is remarkable. Older divers lose less fluid compared to younger divers, which might be related to increased vessel stiffness and especially less relative body water with age. The highest correlation was found for dives with a long surface interval before entering the water. The correlation between fluid loss and repetitive diving of the same profiles and individuals within a few hours was weak, which could be caused by triggered physiological reactions to reduce fluid loss, such as limitation of immersion diuresis and ANP-secretion.

However, we also found a considerable inter- and intraindividual difference in fluid losses of the same individuals and/or dive profiles. Individual parameters like air consumption, prehydration, activity level, health condition, stress and temperature comfort were not related to fluid loss. During a 6-hour-cold-water immersion, Mourot et al. (6) found 2.38 kg fluid loss compared to 2.24 kg in dry immersion, with a twofold higher Noradrenaline level in water immersion. This skin vasoconstrictive effect seems to be less relevant in a standard sports SCUBA dive of usually not more than one hour as in our study. Dive as well as easily accessible individual parameters alone are not suitable enough to estimate dehydration and necessary fluid replacement in SCUBA divers. Although significantly related, dive time and depth alone seem to have very little effect on total fluid loss of divers. Since dive time and depth are related parameters in standard sports diving profiles, only the dive time / time of immersion / time under pressure seems to be relevant. The average mass loss of combat swimmers in a depth of only 3-8 meters over a dive span of 2 hours (2, 5) was the same as in our study whereas divers in saturation diving at a depth of >480 meters (7, 9) lost a maximum of additional 500ml/day only.

From known physiological reactions, only humidification of breathing gas can be related to dive parameters. According to Regulation DIN EN 12021, breathing gas is allowed to have a maximum moisture of 50mg/m^3 =0.05mg/l at 1bar surrounding pressure. It is moisturized in human airways to 45mg/l before it is exhaled in an open breathing system. Despite less moisture capacity in higher surrounding pressure, the total breathing gas consumption during a dive can be taken to calculate the maximum fluid loss from humidification of dry breathing gas. In our study, average consumption of dry air was 1800 liters per dive, thus resulting in a maximum fluid loss of 45mg/l, which is a total of 81ml/dive (105ml/h). Although this amount is remarkably higher than normal fluid loss of around 30ml from surface breathing of ambient air in 1 hour, it contributes only negligibly to the average fluid loss during the first day dive of 1000ml (1.2% relative body weight) in our divers. Confirmed by our results, the measured total air consumption is not significantly related to fluid loss.

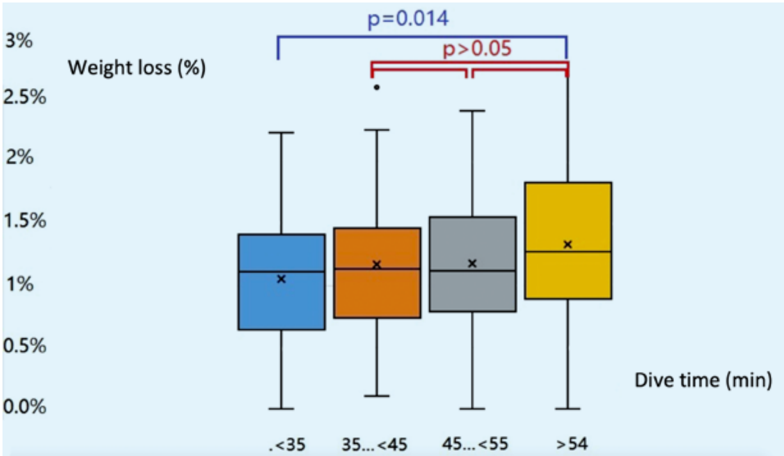

Figure 3

Relative weight loss (% body weight) during first dive and its relation to the corresponding time of immersion are represented in four categories (with approximately equal group size).

Conclusion

Although several mechanisms of fluid loss in SCUBA divers are described, diving seems to be only triggering the physiological response for inter- and intraindividually variable fluid loss. Although we found that fluid loss is increasing with dive time and decreasing with age, diving parameters themselves are not suitable to calculate or predict fluid loss during a particular dive, since fluid loss is intraindividually variable and also increasing with surface interval. Only fluid loss from moisturization of breathing gas is predictable, however, the proportion of this mechanism from total fluid loss is a maximum of 10% only. However, the average fluid loss of about 1 liter per standard sports dive of less than 1 hour is important for sufficient hydration vigilance in order to reduce supersaturation of inert gas and thus reduce the risk of a decompression accident.

Conflict of Interest

The authors have no conflict of interest.

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