Features of gas exchange in advanced level freediver during monofin practice in pool

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PostPrint (draft translation)

Abstract: During a monofin freedive in pool an athlete goes into hypercapnia and hypoxia. This limits his or her performance. During breatholds the air stored in the lungs and airways is changing it’s composition. The changes are poorly studied, or not at all for advanced level freedivers. Some research was done on spearfishers, which is a poor approximation of freediving [4]. We analyzed the end-tidal air of an advanced level freediver in pool training. Continuous freedives under 60% of personal bests, or interval series with each dive under 20-40% of personal best lead to moderate hypoxia and acute hypercapnia and are good for laying-the-bases training periods, increasing personal tolerance to CO2 (though this will not directly improve athletic performance). On the other hand, for pre-competitive training periods for experienced freedivers we recommend continuous one-time dives (with a safety buddy) at distances over 70% of personal best.

Keywords: breath-hold, hypoxia, hypercapnia, freediving.

Aim: analyzing the features of gas exchange in advanced level freediver during pool workout with monofin in interval and continuous sessions.

Methods: literature review, gas analysis, statistics.

Experiment: The research was conducted at the pool of GTSOLIFK Sports University in Moscow. After surfacing, the freediver was breathing into the facemask of Metalyzer 3B R2 Cortex gas analyzer (including his first expiration). Subject freediver: Alexey Molchanov, 9 years of freediving training, 26 years old, bodyweight 80.5 kg, height 180 cm, world records holder. The workloads inducing hypoxia and hypercapnia were: freediving with monofin in a pool to distances of 50, 100, 150 and 200 m with full recuperation and rest times of 6 to 26 minutes, and series of 8 times 50 m dives with short rest intervals of only 5 breaths.

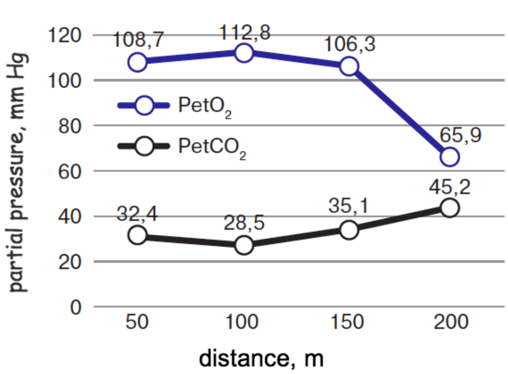

Figure 1: relationship between end-tidal partial pressures of oxygen (PetO2) and carbon-dioxide (PetCO2) and the distance continuously dived by the advanced level freediver with a monofin in a pool

Discussion: The breath air analysis demonstrated that the longer the continuous dive, the lower is PetO2 and the higher is the PetCO2 in the expiration after the workload. The 100 m distance was an exception. It is possible, than the previous 50 m dive played a role of warm-up and did activated the adaptive mechanisms of workout with breathold (fig. 1).

The 1st expiration after surfacing did not measured the biggest change of the expired air composition. Maximum change appeared only after 2-3 breath cycles. The cause is the dead space in the upper airways containing unused air, to which the air from alveoli mixes up during the expiration. The PetO2 and PetCO2 graph sections corresponding to continuous dives to 50, 100, 150 m are slightly bent (fig. 1).

In advanced freedivers the compensatory mechanisms saving oxygen are activated only after a certain level of hypoxemia, instead of doing so gradually as if the need for oxygen would also increase gradually [3]. So at the 150 m to 200 m section of the PetO2 graph, the bend became steep. Probably 200 m was an extreme workout for this freediver, yielding a blood pH shift towards acidification because of CO2 and lactic acid [2]. It made oxygen to become loosely tied to oxyhemoglobin and thus easier released into tissues [1]. In the 2nd expiration after 200 m the PetO2 dropped to a critical 65,9 mm Hg. This is an acute hypoxic state. PetCO2 after the same 200 m dive was increasing up to 48 seconds into recovery breathing, reaching 45,2 mm Hg. Probably such a long period of increasing PetCO2 is due to an important amount of metabolic products from hypoxic workout accumulated in the tissues, and to a gradual passage of CO2 from tissues to bloodstream, and further to the lungs. Thus CO2 continue it's influence on the body long time into the recuperation (Annex 1).

Next is the graph of air analysis in the interval workout of 8 times 50 m (fig.2). Each freedive in the series was 35±2 seconds long. As shown on the graph, hypoxia was moderate.

The graph demonstrates a gradual decrease of PetO2 and a gradual increase of PetCO2. Though after the 4-th dive we see a relatively steep drop in PetO2. Then PetO2 increases after the 5-th dive, and resumes slowly decreasing through the reaming portion of the series. PetCO2 also significantly increases after the 4-th dive, slightly decreases after 5-th dive, and resumes increasing through the remaining dives of the series. Subjectively the athlete felt the 4-th dive as the most difficult of the series. It is possible that during this 4-th dive in the middle of the series the adaptive mechanisms of the body were activated to cope with hypoxic and hypercapnic workout, stabilizing the athlete's state for the remaining part of the workout (fig.2). Thus the recuperation time (5 breaths, i.e. 26±1 sec) was optimal for this athlete. Would it be less, the accumulation of CO2 might have lead to overly acute hypercapnia which in turn might trigger an unbearable urge to breathe.

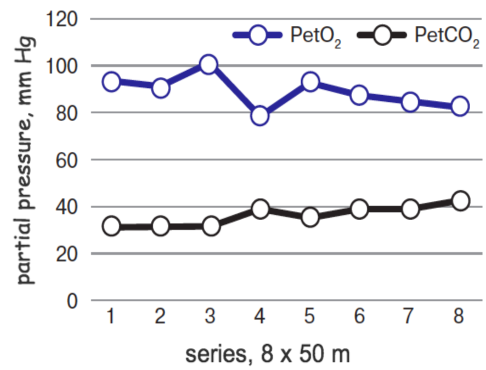

Figure 2: relationship between end-tidal partial pressures of oxygen (PetO2) and carbon-dioxide (PetCO2) at the end of each 50 m dive in a series of 8 times 50 m dived by the advanced level freediver with a monofin in a pool

Conclusions:

1. Oxygen homeostasis was maintained during a repetition of continuous dives to 50, 100, 150 m (i.e. 20%, 40%, 60% of personal best which was 250 m for this freediver). Thus a repetitive routine of continuous dives with complete recovery between dives may be considered safe.

2. Oxygen homeostasis was broken during the pool dive to 200 m distance (which was excessive for this athlete at the time, being 80% of his personal best). It yielded an acute hypoxia and an acute hypercapnia (PetO2 of 65,9 mm Hg, PetCO2 of 45,2 mm Hg). Freediving to distances over 70% of personal best have a risk of consciousness loss (blackout), thus such dives should not be repetitive: only one dive after an easy warm-up (no more than 20-30% of personal best), or eventually without warm-up at all. A trained safety buddy is a must in such freedives.

3. Interval freedives in a series of 50 m (i.e. 20% of the 250 m personal best for this freediver) with a recuperation time constant at about 74% of the dive time, lead to a moderate hypoxia and to an acute hypercapnia (PetO2 82,8 mm Hg, PetCO2 42,2 mm Hg). Such interval training routines with each dive up to 20-40% of personal best can safely improve the threshold of breathold discomfort, which is linked to personal tolerance of CO2. On the other hand such interval training is unable to significantly increase personal best distance in pool freediving.

4. We advise combining the two different methods depending of the training cycle (Annex 2). Interval training is better for preparatory periods laying the foundations of mastery in freediving, while continuous freedives (with a safety buddy) are better for pre-competitive period targeting athletic performance.

All authors have read and approved this paper original publication in 2013, and this 2020 English translation of the original.

Reference (in Russian):

1. Breslav I.B., Nozdrachev A.D., Breathing. St.P., Nauka, 2005
2. Dmitruk A.I. Hyperbaric medicine, St.P., 2004
3. Molchanova N.V. Comparing blood oxygenation in freedivers at different levels of personal bests. N 2, 2005.
4. El Yuri Y., Gas exchange in freediving, St.P., Nauka, 2010

Annex 1 (Raw data which were not included into the Russian 2013 publication, but were provided at the 2013 Hyperbaric Medicine conference in Toulon France. From French powerpoint presentation this is a selective translation of what is missing in the original Russian journal paper above. More raw data will be uploaded to Dataverse Harvard later)

The initial CO2 value of 0,156 L/min was not reached even after 20 minutes of recuperation after the 200 m dive (off the chart below). Because excessive CO2 was stored in tissues, it went out at 2,093 L/min at 46 sec, then 0,394 L/min after 6 min, etc. Thus residual effects of hypercapnia are relatively long during recuperation.

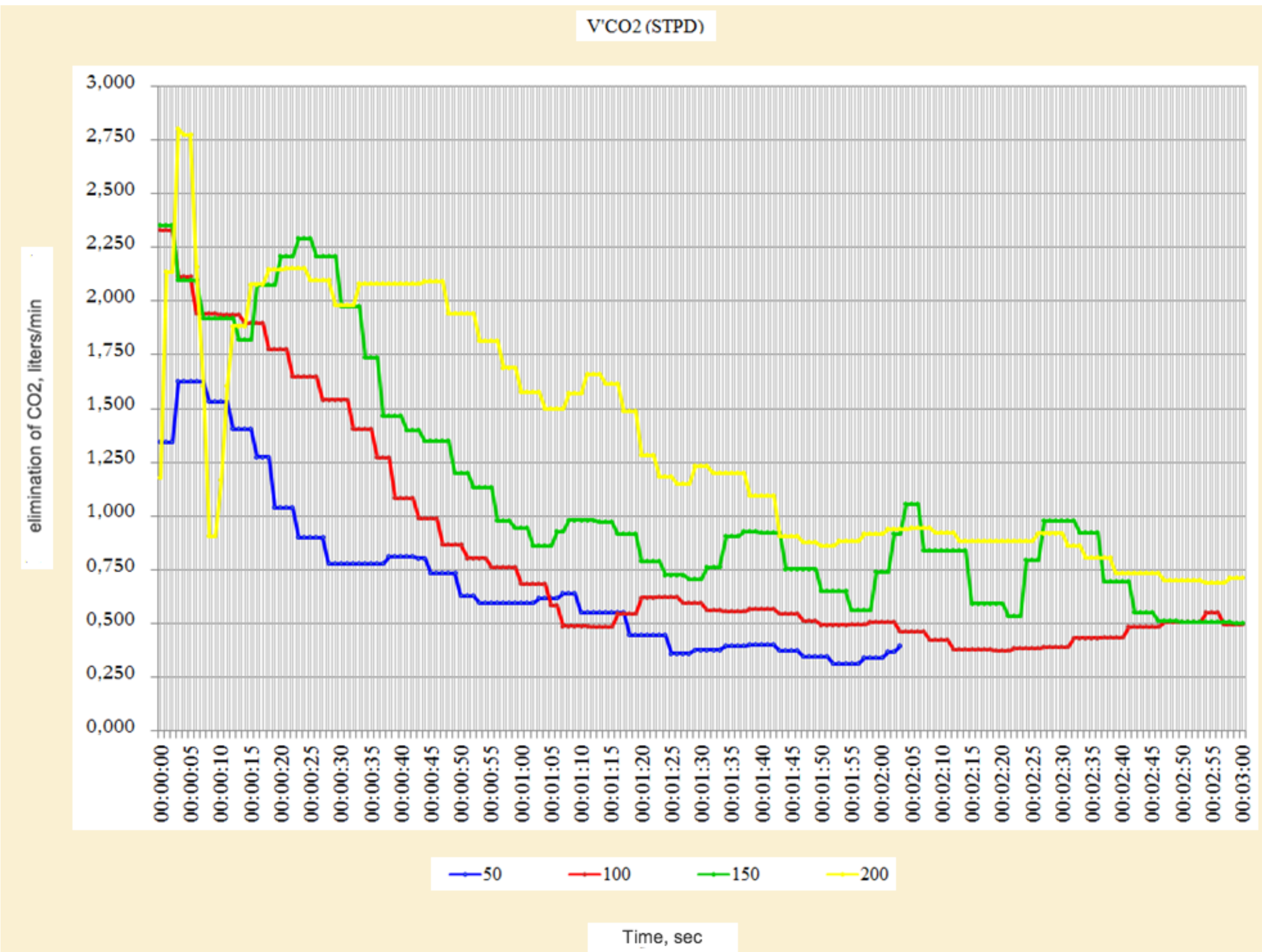

Figure 3: CO2 elimination at recuperation breathing after continuous pool monofin dives by advanced level athlete.

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Figure 4: Research subject: Alexey Molchanov.
Device: "Metalyzer 3B R2" (Cortex).
Measurements: before and after each dive.
Facemask: easy flow, no deadspace. Calibration: before each session.

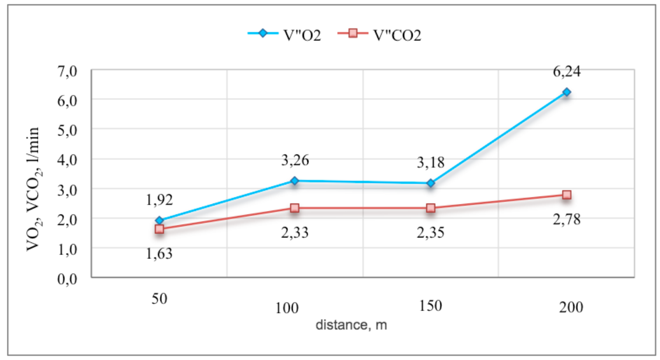

Figure 5: Consumption of O2 and production of CO2 on this graph only correspond to the vital capacity of the lungs. If we would somehow measure the part corresponding to the residual volume, these figures would be higher. Ideally should also be taken into account the O2 stored before the dive in myoglobin, hemoglobin, dissolved in other tissues.

Recuperation from hypoxia is quicker than from hypercapnia. Compared to 50 and 100 m, the recuperation slowed at 150 m (increased consumption of O2 at 2 min after the 150 m dive, green line). After the 200 m (yellow line) an increased consumption of O2 continued though up to 8 min (off the chart below).

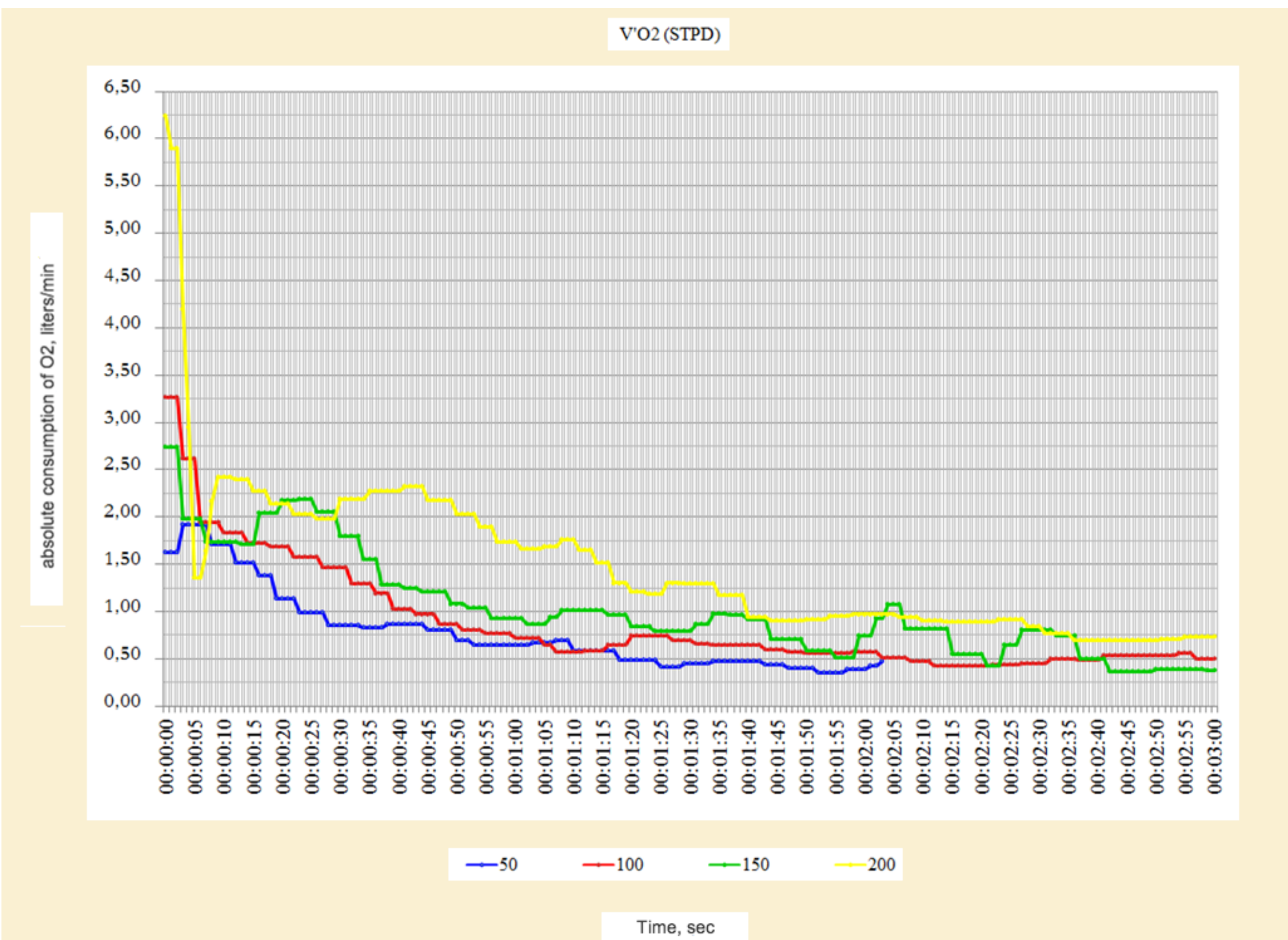

Figure 6: O2 consumption at recuperation breathing after continuous pool monofin dives by advanced level athlete.

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Practical recommendations:

During all the "laying foundations training cycles" use interval training series to increase CO2-tolerance. In particular, for the "beginner training cycles" use series with diving distance 20-30% of personal best and recuperation interval in the "hypoxia intensity zones" level 1 and 2. For "laying foundations training cycles" use interval training series with distances 40-50 % of personal best, recuperation time in intensity zones 3 and 4. High hypercapnia with moderate hypoxia allows a sustained effort with some respiratory discomfort. A reasonable number of dives in a series is to be limited by growing PetCO2 and decreasing PetO2.

We would not recommend increasing further the dive distances in interval series in the "laying foundations cycles", because going over 40-60% from personal best will not give any major improvement in athletic performance. Increasing the interval series distances to even bigger 80% of personal best will not help either, since such dives will limit the realistic volume of training because of excessively long recuperation times between the dives (hence any better tolerance to CO2 will take longer to be achieved).

As for "competitive freediving cycles" we recommend a progressive increasing of continuous dives. It will improve both CO2-tolerance and hypoxic work capability. Such continuous dives training routines though should always be done with a safety buddy because of a possibility of blackout.

Annex 2: For a better understanding of the recommendations section above, this is a short explanation of the training cycles and the hypoxic zones terminology in the context of an overall long-term training plan.

Underwater swims are more or less intense or hard in terms of intensity-zones-of-discomfort (color coded, fig.7). One day or training session is composed of several exercises of swimming on the surface and of breathold swimming underwater, and the graphs below represent daily sums in meters and/or in daily ratios of such exercises. Each tick-label on X-axis although corresponds not to a day, but to a "mesocycle" (from the Greek 'mezos' for 'medium-long-cycle') each in turn made of 4 to 6 weeks i.e. weekly cycles (i.e. microcycles made of training days within one week). Mesocycles in turn are grouped into bigger training periods of one or more "macrocycles": a beginner training period; a "laying foundations" long period stretching over a year or more; and a "competitive freediving" training period or macrocycle (a competition is sometimes being planned after the end of it).

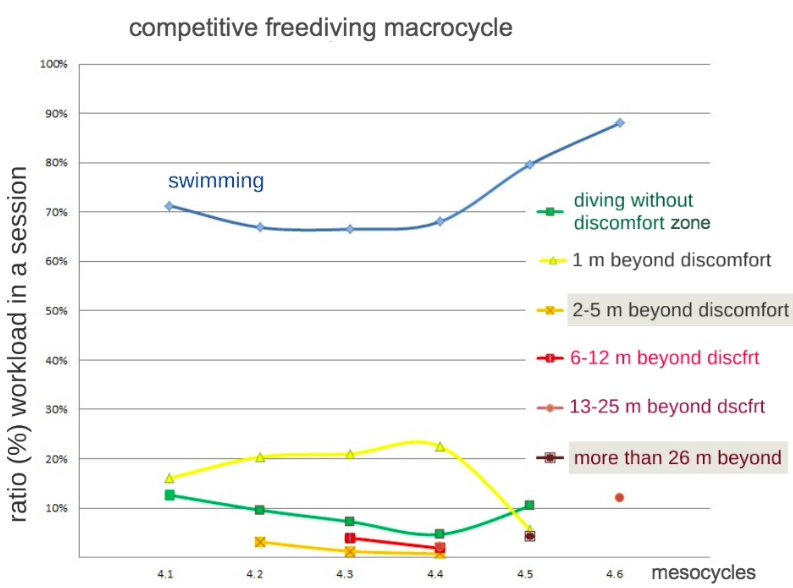

Figure 7: The zones of hypoxic intensity in freediving exercises (illustrated here by a "macrocycle" or "training period" for competitive freedivers)

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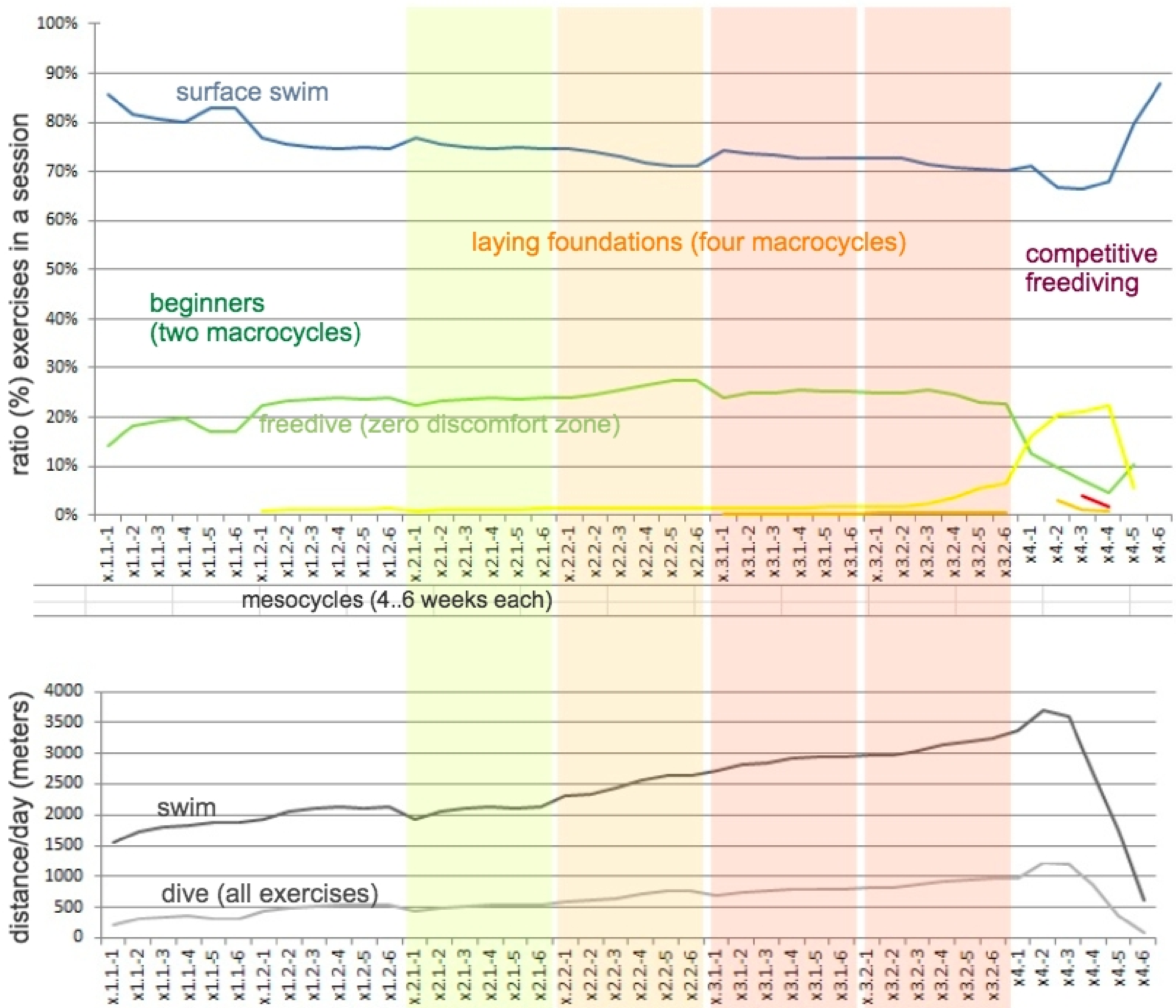

Figure 8: Training cycles illustrated with a training big picture, summed up from the Freediving Federation manual

Annex 3: Who did what and acknowledgments.

The idea and planning of this research was by Dr Molchanova. Also Alexey Molchanov took part in this work as a researcher, as well as a colleague from our IT for Sports lab, Vasily Kuzmichev. We are grateful to them both, although they were not credited as co-authors.

Since this is a postprint, we can also mentioned a later continuation of this research by the same authors published in 2013 and 2014: “Recovering in advanced level athlete after pool monofin freedive” and “Advanced level freediver’s preparatory breathing before a dive”.

If a Federation would plan to translate into English Dr Molchanova’s published scientific articles, the online library at GTSOLIFK Sports University hold many of them. We accounted at least 29 titles (including a couple of non-scientific papers), many in open access.

2005: Interview: how to freedive to 86 m and resurface.

2006: Assessment of athlete readiness.

2007: Heart rate variation in freediving.
2007: Females athletes are winning, males athletes are cumulating experience.

2008: Heart rate variation in freediving.
2008: Aerobic vs anaerobic sources of energy in freediving (blood analysis for better training routines).

2009: Heart rate variation in pool freediving.

2010: Hypoxia in freediving.
2010: Heart rate variation in different phases of deepwater freediving.
2010: Education of freediving instructors. Theory and practical guidelines for sport graduate education, specialization in underwater sports.
2010: Spirometry: comparing packing in advanced vs beginners freedivers.
2010: Psychological and physiological errors leading to blackouts in freediving, a survey and analysis study.
2010: Laying the bases in training of competitive freedivers, PhD in graduate pedagogical sciences thesis.
2010: Laying the bases in training of competitive freedivers, abridged version of the thesis.

2011: Education of competitive freedivers. Theory and practical guidelines for sport graduate education, specialization in underwater sports.
2011: Freediving manual, the basics.
2011: Dynamics of heart rate variation during recovery in underwater sport disciplines.
2011: Heart rate dynamics as a way to assess the readiness of athlete in underwater sports.

2012: Survey and analysis of coping with dangers in freediving and spearfishing.

2013: Freediving manual, the basics.
2013: Theory and practice of freediving for sport graduate education.

2014: Blackouts after the start of the recovery breathing in freediving.
2015: Some personality traits in freediving as a predisposition to blackouts.