Review articles

Aerobic fitness and underwater diving

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Abstract

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Physical fitness is necessary to ensure that the normal and emergent needs of diving can be met. Reserves of both strength and aerobic capacity are important. Aerobic capacity (aerobic fitness or $VO_{2\ max}$) is defined as the maximum amount of oxygen that can be consumed per unit time. Alternatively, it can be described as metabolic equivalents (MET), dimensionless multiples of the oxygen consumption of an assumed resting metabolic rate (3.5 $mL.kg^{-1}.min^{-1}$), yielding a range of 5–25 MET in the healthy population. A minimum capacity as high as 13 MET has been proposed for diving qualification. While limited, the available research data suggest that this is an unrealistically high threshold. A minimum capacity in the range of 7–10 MET may be more appropriate. In recognition of the importance of physical fitness and the decline associated with normal ageing, training programmes should promote awareness of the problems and risks that may be associated with low levels of fitness and the benefits of enhanced fitness. Training to understand and increase aerobic capacity should be encouraged.

Introduction

Poor physical fitness is a growing problem, particularly in more developed nations. The United States Surgeon General Report indicated that more than 60 per cent of adults perform less than the recommended amount of regular physical activity. Approximately 25 per cent of the adult population is classified as completely inactive.[1] Similarly, two-thirds of Canadians aged 22–55 are not physically active enough to meet recommended guidelines.[2]

Body mass index (BMI) is an index of height–weight proportionality commonly used to estimate adiposity. While a rise in BMI can indicate an increase in muscle mass, it more commonly reflects an increase in the body fat fraction, so it has some utility as a population scale estimate. BMI equals weight in kg divided by the square of height in metres. The following categorisation is commonly applied: underweight <18.5 $kg.m^{-2}$; normal weight 18.5–24.9 $kg.m^{-2}$; overweight 25.0–29.9 $kg.m^{-2}$; obese >30 $kg.m^{-2}$. Based on BMI data, obesity in the United States has more than doubled from 1960 to 2004, and now exceeds 33 per cent.[3]

While fitness data are extremely limited for the diving community, high BMI scores establish a basis for concern. Fatality records available to Divers Alert Network (DAN) America include annual BMI-estimated incidence of obesity ranging from 41–55 per cent for 2002–2004 (Figure 1).[4] Medical forms reviewed from Scottish Sub-Aqua Club divers indicated a surprisingly low BMI-estimated incidence of obesity of 2.5 per cent but a significant rise in mean BMI scores from 1991 to 1998.[5] Self-reports of height and weight for 346 Australian club divers responding to a health survey indicated a 12.7 per cent BMI-estimated incidence of obesity.[6]

Physical fitness can be described as a function of strength, flexibility/agility and aerobic capacity. Divers clearly benefit from robust levels of physical fitness. Strength and flexibility/agility are required to don, carry and manipulate equipment, most noticeably through the entry and exit phases of a dive. Aerobic capacity is required to meet the energetic demands of physiological work done pre-dive, at the surface and underwater. The absolute capacities required will vary with the rigour of the environment, the equipment and the nature of the dive. Questions concerning readiness become more important given the general declines of physical fitness observed in the population and the potentially long-term involvement of individuals in diving.

Reserves of both strength and aerobic capacity are important to manage expected and unexpected demands of diving. The adequacy of strength for diving is often evaluated through simple management of equipment on every dive. Aerobic capacity is typically not measured but simply discussed conceptually. This paper will review issues related to aerobic capacity and diving.

The need for aerobic fitness

Adequate physical reserves can be critical when quick, effective responses may keep small problems from becoming serious ones. The draw on cardiorespiratory systems begins with the donning of gear and continues with water immersion and the concomitant shift of blood volume to the central circulation. Little research is available that separates the contribution of stressors such as physically constraining equipment, entry/exit demands, water immersion, breathing resistance, thermal stress, water condition, compression, decompression, buoyancy control, water resistance, psychology and any additional emergent conditions. While difficult to study, the individual and synergistic effects of the stressors must still be managed on every dive.

Robust levels of aerobic fitness reduce the strain produced by diving (or other) stressors. Instead of representing a large portion of the physiological reserve of an unfit diver, the strain represents a relatively smaller portion for the fitter diver. Aerobic fitness may offer additional benefits to divers. While the data are limited, there is some evidence that elevated aerobic fitness can reduce decompression-induced bubble formation in animals and humans and reduce the incidence of serious decompression sickness following provocative exposures in animals.[7–9] Further investigation is required to reconcile these findings with others concluding that aerobic fitness was not related to bubble formation.[10]

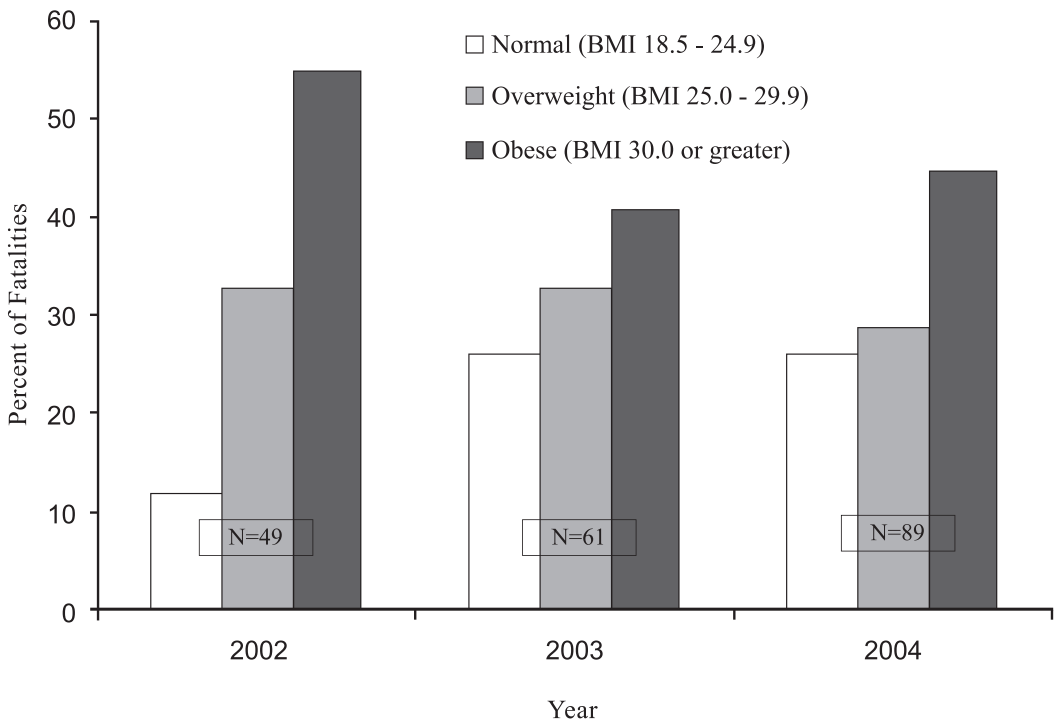
Measuring aerobic fitness

Aerobic fitness (aerobic capacity or $VO_{2\ max}$) can be defined as the maximum amount of oxygen an individual is capable of consuming per unit time. Definitive testing requires the measurement of expired gases throughout a progressive exercise test that ends when the subject can no longer continue. The progression is generally selected so that exhaustion is reached within 8–13 minutes, before issues of thermal stress become a confounder. Such tests are temporarily exhausting, but a relatively quick and non-invasive means of evaluating a key aspect of physical fitness.

Aerobic capacity testing is most commonly completed with treadmill running or stationary cycling. Treadmill tests typically produce the highest values because of greater whole-body involvement. For all but trained cyclists, cycling tests may produce maximal scores 5–10 per cent lower than treadmill tests.[11] Cycling tests may be more appropriate for divers given the similar focus on lower-body exercise. In-water maximal testing is also possible and sometimes available to special groups, but few facilities are set up to do so.

Strategies have been developed to estimate aerobic capacity by a variety of techniques, typically based on regression formulae developed from maximal testing of sample groups. The University of Houston non-exercise (Houston) test, for example, predicts $VO_{2\ max}$ based on height, weight, age and self-reported patterns of physical activity over the previous month on a 0–7 scale.[12] Similar predictive tests have been developed based on submaximal exercise testing. Two of the most well known are the one-mile walk and the up-and-down step tests.[13–16] Predictive tests are generally quite weak on an individual basis. This may be a case of the individual being dissimilar to the group used to develop the formulae. This is a substantial problem for the classic tests that are based on normative data collected 40 to 50 years ago or for

Figure 1
Classification of DAN recreational diver fatalities by BMI ($kg.m^{-2}$) for 2002, 2003 and 2004[4]



tests developed with somewhat idiosyncratic groups. Small deviations in procedure can also have dramatic effects on the prediction. The step test is a prime example, in which a slight variation in the step height will markedly influence the heart rate response and subsequently the estimate. Maximal testing is far superior for true quantification of aerobic capacity. The greatest strength of predictive tests is their field utility. Repeated testing with a standard protocol can be useful to identify patterns of change over time, even if the absolute scores are not accurate.

Classically, $VO_{2\ max}$ was reported as the whole-body rate of consumption of oxygen per minute ($L.min^{-1}$). Problematically, this measure is insensitive to body size, a major source of inter-individual variability. The aerobic fitness of a smaller person is greater than that of a larger person with the same absolute $VO_{2\ max}$. The shortcoming is partially resolved by reporting $VO_{2\ max}$ indexed to body mass, specifically millilitres of oxygen consumed per kg body mass per minute ($mL.kg^{-1}.min^{-1}$). Further resolution is possible by indexing oxygen consumption to lean body mass to discount metabolically inactive fat, although this method is not as widely used.

The numbers and units associated with $VO_{2\ max}$ results may seem unnecessarily complicated to the uninitiated reader. A simpler way to present the results is to use metabolic equivalents (MET). The MET is a dimensionless value describing a subject's aerobic capacity relative to the standard assumed metabolic rate of a resting person (3.5 $mL.kg^{-1}.min^{-1}$). Quite simply, $VO_{2\ max}$ in the same units is divided by 3.5. For example, an individual with a $VO_{2\ max}$ of 35 $mL.kg^{-1}.min^{-1}$ would have a 10 MET capacity (MET_{max}). Gender is not traditionally considered in computing MET values. However, given their normally higher percentage of body fat, women are inappropriately penalised with the standard computation. A correction can be made for females by dividing oxygen consumption by 3.2 instead of 3.5. The normal range of MET_{max} in the healthy population is approximately 5–25 MET. Table 1 lists fitness levels associated with various $VO_{2\ max}$ and MET_{max} capacities.[17]

What level of aerobic fitness has been prescribed for divers?

Minimum swim-test performance is commonly required for entry into dive training programmes. Such tests, however, are a much better indicator of swimming ability than fitness. Minimum MET_{max} capacity can be used as a measure of aerobic fitness to complement medical evaluations and swim-test performance. It has been argued that candidates should have a capacity of 13 MET to be allowed to dive.[18] The basis for this was US Navy research indicating that the maximum speed a fully equipped diver could attain was 1.3 knots (1.8 $km.h^{-1}$) at a work rate of approximately 13 MET. Realistically, this is a demanding standard given the normal level of effort involved with diving. Swimming at a more typical speed of 0.5 knots required an effort of only 3 MET in the same equipment. While emergent conditions may produce a transient demand for great power output, it is unclear if a capacity of 13 MET is a reasonable threshold.

How fit are divers?

While accident data suggest that inadequate fitness is a problem in the diving population, determining the typical fitness level of divers who do not have problems would be informative. Unfortunately, extremely limited data of this type are available. The best insight might come from published research studies involving actual divers for whom aerobic capacity was measured with maximal tests. Table 2 includes a sample of such studies. Representing a range from sport to professional divers, subjects were described as experienced in all but two of the studies.[19,20] The mean aerobic fitness ranged from 37–57 $mL.kg^{-1}.min^{-1}$ (10.6–16.3 MET). The threshold of 13 MET was exceeded by the group mean in only six of the 14 studies described.

The lowest individual $VO_{2\ max}$ score reported was 16 $mL.kg^{-1}.min^{-1}$ (4.6 MET).[24] Inclusion criteria for this study were age greater than 40 years, at least two years of diving experience, completion of at least 10 dives per year with depth greater than 20 metres' sea water, and no previous diving accidents. All of the subjects were French diving instructors. The lowest $VO_{2\ max}$ of a group of sport divers was reported as 16.4 $mL.kg^{-1}.min^{-1}$ (4.7 MET).[8,19] Estimating the minimal individual $VO_{2\ max}$ as the mean minus two standard deviations for the 12 studies in Table 2 that provide means but not minimum values yields a range of 21.0–43.0 $mL.kg^{-1}.min^{-1}$ (6.0–12.3 MET). The median value was 31.9 $mL.kg^{-1}.min^{-1}$ (9.1 MET)

The potential impact of saturation diving on aerobic capacity was evident in one study reporting a 15.2 per cent decline in $VO_{2\ max}$ following saturation dives ranging from 18–28 days total duration, which dropped from 14.8 ± 1.3 to 12.7 ± 1.4 MET.[23] Another study found no significant change in $VO_{2\ max}$ after 19.3 day saturation dives (from 12.1 ± 2.0 to 11.5 ± 2.1 MET).[29] The difference in the activity level of the two groups is unclear but this was likely a factor. Normally, diving does not typically include substantial aerobic demands, thus making it more difficult for active divers to maintain high aerobic capacities.

Table 1
Physical fitness categories[17]

Fitness capacity description	**$VO_{2\ max}$** ($mL.kg^{-1}.min^{-1}$)	**MET_{max}**
Reasonable for inactive lifestyle	>25	>7
Reasonable for modestly active lifestyle	>35	>10
Optimal for lifetime fitness	>50	>14
Athletically competitive	>60	>17
Sub-elite to elite (sport-specific)	>70	>20

How aerobically fit should divers be?

Table 1 describes a capacity of 14 MET as optimal for lifetime fitness. This is a laudable goal for all to pursue. Aerobic fitness typically peaks in the early to mid-20s and will decline thereafter. Statistical models have predicted a decline of one per cent per year for both athletic and sedentary individuals.[32] A longitudinal study revisited individuals at 40 years of age who had been elite athletes at 25 years of age. Those remaining the most active in the intervening years experienced an average decrease in aerobic fitness of 0.7 per cent per year. Those who were least active experienced an average decrease of 1.6 per cent per year.[33] Combining the highest initial level of aerobic fitness with dedicated efforts to slow the rate of decline provides the best strategy for postponing the point at which reduced physical capacity will be incompatible with desired activities.

The age-related decline of fitness is an important issue since diving is a lifetime activity for many enthusiasts. The lack of expiration of basic diving certification allows individuals to continue diving through potentially significant physical changes. The physical capacity possessed in early years may erode substantially over time, though, in many cases, increased skill levels can partially compensate for declining fitness. A skilled diver who maintains excellent neutral buoyancy, good spatial awareness and use of currents, and a high degree of comfort underwater can require dramatically less energy to complete a given dive than a novice might. Not all divers, however, learn to dive early. Those coming

Table 2
Measured aerobic capacity of divers (mean ± SD or median or range)

Lead author (ref)	Divers	Subjects	$VO_{2\,max}$ ($mL.kg^{-1}.min^{-1}$)	MET_{max}	Mode	Age (yr)	BMI ($kg.m^{-2}$)
Thompson (1984a)[21]	Commercial	148 M	46 ± 9.0	13.1 ± 2.6	?	30 ± 5	25 ± 3
Thompson (1984b)[22]	Commercial	10 M	43.8 ± 4.5	12.5 ± 1.3	?	?	?
Thorsen (1990)[23]	Experienced	18	51.7 ± 4.6*	14.8 ± 1.3	Treadmill	28 (mean) (23–34)	24.3†
Carturan (2002)[19 ‡]	Sport	45 M	38.9 ± 10.8	11.1 ± 3.1	Cycle	37 ± 9.6	25.5†
Dujic (2004)[10]	Experienced	13 M	47.8 ± 4.7	13.7 ± 1.3	Treadmill	29.9 ± 5.0 (22–38)	21.5–29.0
Tripodi (2004)[24]	Experienced	27 M / 3 F	37 ± 8	10.6 ± 2.3	Cycle	48 ± 7.5	25.5†
Dujic (2005a)[25]	Military	10 M	41.2 ± 6.3§	11.8 ± 1.8	Cycle	35.1 ± 4.3 (29–41)	22.5–29.0
Dujic (2005b)[26]	Croatian Navy	12	41.2 ± 6.3	11.8 ± 1.8	Cycle	34.7 ± 4.1 (29–41)	25.8 ± 2.2 (22.2–29.0)
Almeling (2006)[20]	Certified	28 M	27.4–47.7‖	7.8–13.6	Cycle	39.9 (26–62)	24.4†
Dujic (2006a)[27]	Military	7	41.5 ± 9.6	11.9 ± 2.7	Cycle	30–39	25.9 ± 2.0
Dujic (2006b)[28]	Experienced	10 6	41.8 ± 6.4 47.3 ± 5.3	11.9 ± 1.8 13.5 ± 1.5	Cycle Cycle	34.4 ± 4.2 32.2 ± 5.2	25.9 ± 2.0 26.5 ± 2.4
Thorsen (2006)[29]	Commercial/ Saturation	8 M	42.3 ± 7.1	12.1 ± 2.0	Treadmill (6) Cycle (2)	41 (median) (29–48)	28.6 (median) (24.2–30.7)
Blatteau (2007)[30]	Trained military	16	51.7 ± 8.3	14.8±2.4	Treadmill	33.6 ± 3.7 (27–39)	21.0–27.1
Boussuges (2007)[31]	Trained military	20 M	57 ± 7	16.3 ± 2.0	Treadmill	33 ± 4	25 ± 2

* $VO_{2\,max}$ in $mL.kg^{-1}.min^{-1}$ derived from reported mean $L.min^{-1}$ by using the reported mean weight of subjects
† BMI derived from reported mean mass and mean height of subjects
‡ Study included individual data reported previously[8]
§ Mean $VO_{2\,max}$ reported in the text differed from the mean computed from the individual values also provided in the paper (the latter is shown here)
‖ $VO_{2\,max}$ imputed from minimum and maximum whole body measures ($L.min^{-1}$) converted to relative using the minimum and maximal body mass values, respectively, reported for the group

to diving later in life, when fitness may be more of an issue, may not benefit from the economy of experience. Similarly, other individuals may never develop high competence because of infrequent participation or personal limitations. Less physically competent individuals will be under much greater physiological and psychological stress.

The question of a reasonable requirement for aerobic fitness to dive is a difficult one when confounded by issues of experience. This was strongly debated more than 20 years ago when the recommendation for a minimum aerobic capacity of 50 $mL.kg^{-1}.min^{-1}$ (14.3 MET) for North Sea divers was suggested.[21,22,34,35] While the highest fitness possible is undoubtedly desirable, setting valid minimums is difficult. The French diving instructor with a $VO_{2\ max}$ of 16 $mL.kg^{-1}.min^{-1}$ (4.6 MET)[24] described previously certainly presented a fitness level that most would deem insufficient, but deciding on a single value is not as straightforward as it might seem. The available data suggest that at least some individuals are diving, presumably with an expectation of safety, with aerobic capacities far below the 13 MET threshold promoted by some.[18]

I posit that a skilled diver can probably safely conduct an uncomplicated dive under benign to modest conditions with a capacity of 7 MET. This is not optimal, but a skilled diver might be expected to have a reasonable reserve to meet most typical demands. Recognising the possibility of exceptional challenges, the benefit of substantial reserves and the greater challenge of less experience, I recommend that divers maintain a capacity of 10 MET or greater. The recommendation should be treated as a rule for anyone in a leadership position with responsibility over others. Interpreted conservatively this would include all buddy diving situations. For training purposes, I advocate accepting students with a capacity of 7 MET for confined water work and including conditioning in their training to help them achieve a 10 MET capacity before the open-water phase; advancement to open water may be delayed. MET scores should also be computed with gender-appropriate values, using assumed resting metabolic rates of 3.5 $mL.kg^{-1}.min^{-1}$ for males and 3.2 $mL.kg^{-1}.min^{-1}$ for females.

Physical fitness should receive more attention than is the current practice in dive training and diver evaluations. The risks of inadequate fitness and the benefits of enhanced levels of fitness for diving and general health should be more thoroughly discussed. All divers should be encouraged to pursue a capacity of 14 MET or higher as a personal goal (Table 1). At the same time, setting a threshold limit that is unrealistic serves no positive purpose. The majority of the studies described in Table 2 involved professional divers, one-third of them military divers with regular physical fitness training obligations. While the data are not available, it is likely that many divers, professional and non-professional, will have lower aerobic fitness than the described divers and will continue to dive safely. The point at which low aerobic fitness actually becomes a significant independent risk factor for diving safety requires additional study, but it is likely at the bottom of or below the range of 7–10 MET.

Practical strategies for testing of aerobic capacity

A major argument against aerobic capacity testing will be financial; testing in a professionally staffed facility can be expensive. One strategy to avoid the high cost is to volunteer for research studies that include $VO_{2\ max}$ tests as part of the protocol. These are typically available through the exercise or applied physiology programmes of many universities and colleges. Participants can have their performance evaluated while contributing to the greater good.

Practically, maximal testing may be required only for those with a poor history of regular physical exercise or those expected to be at risk of inadequate capacity. The pencil-and-paper tests mentioned earlier may not provide reliable estimates of aerobic fitness on an individual basis, but they can be a useful first step in discussing fitness questions. Some responses can be instantly reassuring. For example, any individual regularly completing a five kilometre run without breaking pace in less than 30 minutes is likely to have sufficient aerobic capacity. Conversely, responses that indicate less than regular involvement in physical activity with an aerobic component should prompt closer scrutiny. Unfortunately, many activities are more difficult to assess than running. Interpreting times and distances for cycling and swimming, for example, requires more caution. Fast swim times may say more about skill than aerobic fitness (and sometimes of fond memory). Outdoor cycling performance is affected by the bicycle, additional load and surface conditions, but participation weighs heavily in favour of the candidate. Reports of stationary cycling activity are the least informative. The resistance settings are selected by the rider, and frequently on non-standard scales. Cycling for even long periods of time against very low resistance will not maintain fitness. Giving too high a fitness credit for indoor cycling is a common problem. Reports of use of a wide range of other modern gym equipment can be similarly misleading.

The use of predictive tests to grade relative performance was discussed earlier. This approach can be useful for applied diver testing. Bias due to personal skill is likely to be less apparent in fin swimming than standard swimming strokes. A simple and relevant challenge is to have divers complete a surface fin swim with mask and snorkel alone or with mask and snorkel while wearing unused scuba gear. The time to complete the swim, heart rate at the end and heart rate one minute after ending exercise would all be recorded. Reduced swim times could indicate improvements in skill, economy or cardiorespiratory fitness. Increased difference in heart rate immediately after exercise and one minute post-exercise, i.e., better recovery of the heart rate, would primarily indicate improved cardiorespiratory fitness. Instituting such challenges to every training session may help divers establish the habit of regularly reviewing their own fitness.

Effectiveness of aerobic training

Aerobic capacity is sensitive to training. $VO_{2\,max}$ can generally be increased by 25 per cent or more in untrained individuals with modest effort. Additional gains can occur as body composition changes and the ratio of muscle-to-fat mass is improved. There are two primary stages of adaptation. The first comes after two to three weeks of training, primarily in the form of an increase in body fluid volume. The second begins after six weeks of training as the metabolic potential within the muscle cells is increased.

The primary adaptation to regular aerobic exercise is an increased work capacity. This increases the reserve potential to meet emergent needs and reduces the strain on the cardiorespiratory system from any submaximal work rate.

A similar pattern of detraining will be experienced if a training programme is suspended. The fluid volume increase will be lost within the first two weeks and a decline in the metabolic readiness will follow. Fortunately, the same degree of effort required to improve aerobic fitness is not required to maintain it. Maintenance training that is of lesser duration but similar intensity can protect aerobic capacity.

Training initiatives

The most basic goal should be to participate in some form of physical activity most days of the week, achieving training intensity efforts three times per week for 30–60 minutes per session. The simplest means of monitoring exercise intensity is based on the percentage of maximal heart rate (HR_{max}). Age-estimated maximum heart rate (assumed to be 220 minus age in years for land-based activities) is computed, and a target range of exercise intensity established (usually between 70 and 90 per cent of HR_{max}). This range corresponds to approximately 55–75 per cent of $VO_{2\,max}$. Immersed exercise heart rates will be lower than during land-based exercise, but similar training targets can be established by tolerance.

Individuals are encouraged to maintain their exercise intensity at the low end of the target range when they are starting out. The top end of the range represents the maximal safe intensity for sustained exercise. As fitness increases, it will take a greater intensity to generate the same relative effort (i.e., to produce the same heart rate or percentage of maximal ability). Employing a variety of aerobic activities is generally desirable to reduce the risk of overuse injury and boredom. A mix of activities that also incorporates strength, flexibility and agility will also produce benefits useful to meet the demands of diving.

The greatest absolute improvement in $VO_{2\,max}$ would likely be seen with running or cycling. Water-based activities, however, in addition to generally being less mechanically stressful, allow simultaneous improvement of physical fitness, watermanship and in-water psychological comfort. Fin swimming should be an important part of any programme given the diver's reliance on finning. Length fin swimming might be most appropriate at the entry level. Advancing to underwater hockey or underwater rugby introduces a dynamic component that can have a powerful training effect on fin power, technique and, as a separate but very relevant benefit, breath-hold ability. Regular swimming offers similar benefits in watermanship and develops upper-body strength, important for entry/exit requirements and many emergent situations. Advancing to water polo or canoe polo can again add more of a dynamic and social component to the fitness effort.

Conclusions

Physical fitness is necessary to ensure that the normal and emergent needs of diving can be met. Reserves of both strength and aerobic capacity are important. A minimum capacity in the range of 7–10 metabolic equivalents (MET) may be more appropriate than the capacity of 13 MET sometimes advocated. In recognition of the importance of physical fitness and the decline associated with normal ageing, training programmes should promote awareness of the problems associated with low fitness and the benefits of enhanced fitness. Possession of a healthy fitness reserve can make a huge difference in how well normal and emergent events will be managed. Such preparedness is clearly of value to divers operating in a medium (water) that at times and unexpectedly can be very unforgiving.

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