



Available online at
ScienceDirect
www.sciencedirect.com

Elsevier Masson France
EM|consulte
www.em-consulte.com/en



GUIDELINES

Recreational scuba diving in patients with congenital heart disease: Time for new guidelines



Plongée sous-marine de loisirs chez des patients ayant une cardiopathie congénitale : mise à jour des recommandations

Jean-Marc Schleich^{a,b,*}, Frédéric Schnell^c,
Benoît Brouant^d, Gerald Phan^e, Vincent Lafay^f,
Laurent Bonnemains^g, Marc Bédossa^a

^a Rennes University Health Centre, Cardiology and Vascular Diseases Division, Rennes, France

^b Inserm, U1099, université de Rennes 1, LTSI, Rennes, France

^c Rennes University Health Centre, Sports Medicine Division; Physiology Laboratories, Rennes-1 University, Rennes, France

^d Mediwald, Creutzwald, France

^e Levallois-Perret, France

^f Marseille, France

^g Paediatric and Congenital Cardiology, Strasbourg University Health Centre, Nouvel Hôpital Civil, Strasbourg, France

Received 28 October 2015; received in revised form 9 February 2016; accepted 11 February 2016
Available online 27 June 2016

KEYWORDS

Congenital heart disease;
Scuba diving;
Recreational underwater diving;

Summary The number of recreational scuba divers is steadily increasing. In its latest recommendations, the French Federation of Undersea Studies and Sports listed congenital heart disease as a formal and final contraindication to scuba diving. On the other hand, with the progress made in their management, the prognosis and quality of life of patients with congenital heart diseases have improved considerably, enabling them to engage in physical and sports endeavours, which are known to confer general health and psychological benefits. As a

Abbreviations: CHD, congenital heart disease; FFEISSM, French Federation of Undersea Studies and Sports; LV, left ventricular; MET, metabolic equivalent; O₂, oxygen; RV, right ventricular; VO₂, O₂ consumption.

* Corresponding author. Rennes University Health Centre, Hôpital de Pontchaillou, Cardiology and Vascular Diseases Division, 35033 Rennes, France.

E-mail address: jean.marc.schleich@chu.rennes.fr (J.-M. Schleich).

<http://dx.doi.org/10.1016/j.acvd.2016.02.003>

1875-2136/© 2016 Elsevier Masson SAS. All rights reserved.

Water sports;
Health
recommendations

consequence, the ability of these patients to dive has become a regular and recurrent issue. We review the various types of scuba diving, the physical performance required for its practice, its effects on cardiovascular function and the elements that need to be considered before recommending whether it can be practiced safely at various levels of difficulty. Because of the diversity and broad heterogeneity of congenital heart diseases, a detailed evaluation of each patient's performance based on clinical criteria common to all congenital heart diseases is recommended.

© 2016 Elsevier Masson SAS. All rights reserved.

MOTS CLÉS

Cardiopathies
congénitales ;
Plongée
sous-marine ;
Sports aquatiques ;
Recommandations
médicales

Résumé Le nombre d'adeptes aspirant à la pratique en loisir de la plongée sous-marine en scaphandre s'accroît. Dans les dernières recommandations de la Fédération française d'études et de sports sous-marins, les cardiopathies congénitales font parties des contre-indications définitives à la pratique de cette activité dans la liste éditée par la Commission médicale et de prévention nationale. Parallèlement, en raison des progrès dans leur prise en charge, le pronostic des cardiopathies congénitales a considérablement été amélioré. La cohorte de patients ne cesse d'augmenter. Leur qualité de vie a aussi été améliorée, leur permettant de prétendre et d'accéder aux activités physiques et sportives desquelles on connaît les effets bénéfiques. La question de l'aptitude à la plongée se pose donc de plus en plus souvent. Nous revoyons les différents types de plongée, les performances physiques nécessaires à leur pratique, leurs effets sur les fonctions cardiovasculaires et les éléments médicaux devant être pris en compte pour autoriser sa pratique à différents niveaux de difficulté. En raison de leur diversité et d'une importante hétérogénéité au sein même d'un groupe de cardiopathies congénitales, nous proposons pour chaque patient une évaluation précise de son aptitude à partir de critères cliniques et paracliniques communs à l'ensemble des cardiopathies congénitales.

© 2016 Elsevier Masson SAS. Tous droits réservés.

Background

A consequence of the growing access to scuba diving is an increase in the number of followers of this recreational, fun and contemplative athletic activity. According to the latest recommendations by the French Federation of Undersea Studies and Sports (FFESSM) published in 2012 [1], congenital heart disease (CHD) is a formal and final contraindication to scuba diving. On the other hand, with the progress made in their surgical as well as percutaneous catheter management, the prognosis of patients with CHD has improved considerably [2]. As a result, the population of adolescent and adult patients continues to grow at a rate of 5% per year, surpassing the number of children for the past 10 years [3,4]. In France, approximately 150,000 adults currently have CHD. Besides the increase in their number, their quality of life has improved, enabling them to attempt—and often succeed—in engaging in physical and sports endeavours, which are well known for conferring general health and psychological benefits [5,6].

Because the issue of aptitude to engage in scuba diving presents itself regularly, we felt the need to reflect on the matter, with a view to contributing decisive elements for or against the practice of this activity. These thoughts address recreational diving exclusively, and exclude all commercial and military divers, whose medical supervision is specific.

Furthermore, some valvular diseases, systemic hypertension and coronary heart disease, independent of their possible congenital origin, are often definitive contraindications to the practice of scuba diving. Therefore, we refer the readers to the existing recommendations for these disorders [7].

The anatomical presentation of CHDs is highly variable; they may, consequently, be responsible, alone or in combination, for shunts, valvular stenosis or regurgitation, myocardial disease, pre- or postcapillary (or mixed) pulmonary arterial hypertension, dilatation of the aorta, pulmonary artery or both, and atrial or ventricular arrhythmias or conduction disorders [8]. This variability complicates the formulation of recommendations based on the usual and traditional classification of CHD as shunts, left or right stenosis, valvular diseases and others. Within each group of CHD, the anatomical and, consequently, clinical presentations are highly heterogeneous, which mandates for each patient a precise evaluation of each constitutional malformation. Inspired by Budts et al. [9], we formulated our recommendations on the basis of elements that are common to all CHDs, from which each individual can be separately evaluated. The importance of considering, for each patient, several extracardiac factors, including pulmonary, thoracic and haematological disorders, as well as therapeutic interventions, cannot be overemphasized [10].

Types of scuba diving included in these recommendations

These recommendations are limited to recreational open-circuit scuba diving. The gas used is room air or a <40% enriched nitrox-like mixture and a ≤ 1.6 bar oxygen (O_2) partial pressure. The use of recycler systems and complex gas mixtures, including trimix, is excluded from this discussion. The dives must observe the prerogatives of each level, according to the rules published in the technical training manual issued by the National Technical Commission of the FFESSM [11], using a validated decompression procedure (MN90 tables or dive computer) and a limit of no more than two dives daily. Divers with CHD are expected to follow the medical instructions. A state-designated physician is responsible for the delivery of a certificate confirming the absence of contraindications based on specific considerations (detailed below). The possible restrictions, with respect to the diver's prerogatives, must be explicitly visible on the certificate handed to the patient, specifically applying the model prepared by the FFESSM [12], which includes a "special observations" section. Depending on the type of heart disease and possible sequelae, nitrox dives might be authorized upon the advice of a state-designated physician.

Cardiovascular effects of underwater dives

Underwater dives cause haemodynamic, thermal and ventilatory changes, which may cause the decompensation of a well-tolerated pre-existent heart disease [13,14]. As soon as immersion begins, most of the hydrostatic pressure exerted over the entire immersed body is transmitted by the tissues to the adventitial side of the vascular walls, with a passive transfer of blood toward the central circulation, causing a rapid increase in left ventricular (LV) preload [15,16]. The increase in preload increases cardiac output via the Frank-Starling mechanism. The atrial and ventricular distension resulting from this sudden increase in preload may promote the development of arrhythmias during the dive [17]. A compensatory increase in the secretion of natriuretic peptides in response to this relative hypervolaemia, caused by dilatation of the cardiac chambers, gradually increases the diuresis, resulting in a relative hypovolaemia at the end of the dive. Furthermore, the immersion exposes the trunk and extremities to the cold, increasing peripheral vasoconstriction, systemic blood pressure and ventricular afterload [15]. Vasoconstriction also promotes the central redistribution of the blood volume, further increasing the immersion diuresis. These specific thermal limitations must be taken into consideration when setting individual restrictions.

Ventilation is also modified during dives in autonomous scuba diving. The regulator equalizes the gas and the ambient hydrostatic pressures, which strive to overcome strong inspiratory and expiratory resistances, in the presence of large differences between inspiratory and expiratory pressures. As the dive deepens, the volumetric mass of inhaled gas increases, increasing the dynamic resistance to flow across the airways and the ventilatory effort, which might promote hypercapnoea from alveolar hypoventilation by increasing the end-expiratory volume.

During the period of desaturation, bubbles circulating in the pulmonary vascular network increase pulmonary vascular resistance, further augmenting the stress imposed on the right ventricle [18]. While these bubbles are usually silent and harmless, they might be the source of air embolism in case of excessively rapid decompression. An atrial or ventricular septal defect with right-to-left shunt, present in some CHDs, increases the risk of paradoxical air embolisms.

In conclusion, the cardiovascular system must undergo multiple adaptations during immersion and hyperbaric conditions. The stress involved depends on the kind of dive, the work accomplished, the means of decompression, the equipment used and the amount of exposure to cold. These specific factors must be addressed by the state-appointed physician and mentioned on the certificate of clearance.

Amount of physical activity (or exercise capacity) involved in underwater diving

The intensity of physical activity and energy expenditure can be measured by O_2 consumption, expressed in metabolic equivalents (MET), compared with the baseline metabolism (at rest, 1 MET = 3.5 mL/kg/min of O_2 in men and 3.2 mL/kg/min of O_2 in women) [19].

The energy consumed in underwater diving remains controversial. A capacity of approximately 4 MET is required for simple recreational diving, while 6 MET provides a safe and desirable margin for this activity [20,21]. However, the energy consumed varies widely with the water temperature, the equipment available, the currents encountered, the surface swimming as well as the environmental conditions [22]. In the "Compendium of Physical Activities" compiled by the University of Arizona [23], underwater diving was attributed 7 MET, a value found among the publications listed on that site and, therefore, adopted by the authors.

A physical activity sustained under stable aerobic conditions for more than 50–60 minutes must be performed below the first ventilatory threshold, usually near 50% of peak O_2 consumption (VO_2), which can be measured during cardiopulmonary exercise [24]. The first ventilatory threshold of a candidate diver should, therefore, be ≥ 6 MET in order to remain below that threshold during a dive performed under stable physical conditions [20]. This generally corresponds to a ≥ 12 MET maximum exercise capacity [25].

Based on the article published by Mitchell et al. [21], this exclusively recreational activity could be authorized by the state-appointed physician under strictly limited and clearly defined conditions, in patients whose first ventilatory threshold is > 4 MET (peak $VO_2 > 28$ mL/kg/min in men and > 25.6 mL/kg/min in women). This proposal would contribute some flexibility and a range of decisions applicable according to the context.

Published recommendations on the practice of physical activities in patients with CHD

The virtues of physical activity and training in patients with CHD are well known [26]. A routine particularly adapted to a physical activity increases exercise capacity without

adverse or fatal consequences [27]. After the institution of a retraining programme, quality of life scores are improved.

Recommendations were formulated in 2004 by Maron et al. regarding the physical activity and the recreational and competitive sports practiced by patients with cardiovascular disorders of exclusively genetic origin [28]. Distinctions were made between the practice of recreational versus competitive sports, emphasising the greater difficulty in formulating recommendations pertaining to recreational activities. In that publication, scuba diving was included among low-intensity (<4MET) activities, while swimming was classified as a moderate-intensity (4–6MET) activity.

In 2005, the Task Force 2 of the 36th Bethesda Conference defined criteria for each CHD, pertaining to the exclusively competitive practice of sports [29]. The term ‘‘athlete’’, which corresponds to intense training (i.e. exceeding the limit of breathlessness for ≥ 8 h per week over >6 months) is beyond the scope of this discussion. In the same year, experts from the European Society of Cardiology published their recommendations pertaining to patients presenting with CHD, also discussing exclusively competitive sports activities at an amateur or professional level [30]. With respect to specifically recreational physical activities, the first recommendations were published by experts from the European Society of Cardiology in 2006 [6]. Underwater dives are listed as a contraindication in presence of residual interatrial shunt across an atrial septal defect or a patent foramen ovale, because of the risk of paradoxical embolism.

More recently, Takken et al. [31] detailed the physical activities and sports recommended for each CHD. These authors maintain that, unlike competitive physical activities, those called recreational are characterized by exercises undertaken without personal or external pressure; therefore, the subject may discontinue or slow the physical activity as desired. As emphasized by the authors, this does not apply entirely to even recreational scuba diving, because of the risks related to the aquatic environment. The recommendations made are with respect to the CHD, without specific consideration of the type of physical activity, particularly in that environment.

Finally, all these recommendations formulated by sports medicine specialists and cardiologists are not based on randomized studies—rather on the opinions of a majority of experts. As a consequence, the writing is usually prudent, appearing at times excessive, when ultimately prohibiting scuba diving to all those with CHDs. Upon scrutinizing these articles, and taking into consideration possible concomitant extracardiac disorders, the anatomical—and hence clinical—diversity of CHD, even within so-called ‘‘homogeneous’’ groups of cardiac malformations, and the specific nature of scuba diving, we recommend an individual risk evaluation from an ensemble of clinical and paraclinical less-specialized criteria, allowing or disallowing this activity, regardless of the CHD.

Regulatory aspects of the medical certificate

In France, sports participation inside a federation requires, when a first licence is attributed, the presentation of

Table 1 Cardiovascular status evaluation.

<i>Left ventricular ejection fraction (%)</i>	> 50
<i>Right ventricular fractional shortening (%)</i>	> 35
<i>Tricuspid annular plane systolic excursion (cm)</i>	> 16
<i>S' wave (cm/s)</i>	> 10
<i>Septal thickness (mm)</i>	
Men	< 13
Women	< 12
<i>Left ventricular diameter (mm)</i>	
End-diastolic, men	< 56
End-diastolic, women	< 52
End-systolic, men	< 41
End-systolic, women	< 37
<i>Gradient (mmHg)</i>	
Mean aortic valve	< 20
Maximum pulmonic valve	< 30
Maximum left intraventricular	< 30
<i>Mean pulmonary artery pressure (mmHg)</i>	< 20
<i>Ascending aorta diameter (mm)</i>	< 45
<i>Transcutaneous arterial saturation (%)</i>	> 95
<i>Maximum functional capacity (MET)</i>	> 8
<i>First ventilatory threshold (MET)</i>	> 4

MET: metabolic equivalent.

a <1-year-old medical certificate of clearance (article L. 231-2-2 of the French sports code). For disciplines with specific risks (defined in article L. 231-2-3 of the French sports code), the medical certificate can be granted only after an in-depth examination by a physician qualified as defined by the federation.

As the disorder is congenital, the presence of heart disease will be an issue with the first licence application. For the FFESSM, certificates for non-competitive activities, before the attribution of the first licence, may be written by any physician. The use of an official certificate that lists the specific contraindications related to that activity [12] is nevertheless recommended.

The aim of these recommendations is not to remove CHD from the list of contraindications; instead, they are marked by an asterisk (*) as a ‘‘disease to evaluate’’, in which case the state-accredited physician is the only authorized signatory of the certificate.

At the first stage, the patient’s cardiovascular status is evaluated by a cardiologist, based on the criteria listed in the [Tables 1 and 2](#), and regular cardiology follow-ups are scheduled for that patient. Based on that evaluation, at the second stage, the state-accredited physician prepares a ‘‘no contraindication to scuba diving’’ medical certificate, specifying possible limitations to the various types of dive. The physician responsible for writing the certificate must examine the patient personally, even if this has already been done by a colleague.

To respect medical confidentiality and with the patient’s consent, it might be valuable to collect cases anonymously, with a view to following the population prospectively, validating these recommendations and, if necessary, adapting them.

Table 2 Cardiovascular status evaluation: exercise testing.

Absence of functional manifestations
Maximum functional capacity > 8 MET/first ventilatory threshold > 4 MET
Normal adaptation of systemic systolic blood pressure, defined as an increase of > 20 mmHg
Absence of major arrhythmia, prolonged asystole or change in repolarization
Transcutaneous oxygen arterial saturation > 95%

MET: metabolic equivalent.

Evaluation of cardiovascular status

This evaluation of cardiovascular status is restricted exclusively to the patient's regular cardiologist, based on the observations made during long-term follow-up and on the results of the laboratory tests usually ordered for this kind of heart disease. A standard questionnaire may be used to define the patient's functional status, as the completion of a questionnaire seems more informative than a mere history taken by the physician [32]. A systematic review of all medications will be recorded, along with a search for cardiovascular risk factors and functional symptoms, including chest pain, dyspnoea, palpitation and fainting, especially during exercise. A sample questionnaire can be accessed and downloaded from the website of the *Société française de médecine de l'exercice et du sport* (French Society of Exercise and Sports Medicine) [33]. The questionnaire must be dated and signed by the applicant.

A systematic and detailed cardiovascular physical examination must be performed, along with complementary tests, including a 12-lead electrocardiogram, to search for signs of hypertrophy, abnormal conduction or repolarization, or arrhythmias. A <6-month-old 24-h ambulatory electrocardiogram must be recorded, even in absence of arrhythmic symptoms, after having asked the patient to engage in physical exercise for ≥ 1 hour, followed by a period of recovery during recording. Ambulatory electrocardiograms cannot currently be recorded in water for clinical purposes.

Echocardiograms play a prominent role in the evaluation of these patients, to measure chamber dimensions, wall thickness, ventricular systolic function, the severity of valve regurgitation and the dimensions of the great vessels, particularly the aorta. Pulmonary arterial pressures are measured by the Doppler method. Should these measurements be problematic, they can be replaced by other imaging techniques, mostly magnetic resonance and computed tomography scans.

Exercise testing with measurements of VO_2 is a reliable means of evaluation of exercise capacity in patients presenting with CHD [34]. Performed on a treadmill or a bicycle ergometer, the test measures peak heart rate, maximum VO_2 (in mL/kg/min) and first ventilatory threshold. Systemic blood pressure and transcutaneous arterial oxygen saturation should also be measured during exercise and recovery. While it is critically important, exercise testing in

the laboratory does not faithfully reproduce the stress of a natural setting, particularly that encountered while diving.

After that evaluation, asymptomatic applicants are eligible if the results detailed below have been achieved (see also Tables 1 and 2).

Results required on echocardiogram or by another imaging technique

1. LV ejection fraction > 50% [35,36]; in case of systemic right ventricle, and in the absence of established normal values, systolic function is defined as normal on the basis of criterion No. 7.
2. LV wall thickness < 13 mm in men and < 12 mm in women [37,38].
3. Absent, minimal or moderate valvular regurgitation with an end-diastolic LV diameter of < 56 mm in men and < 52 mm in women, and an end-systolic LV diameter < 41 mm in men and < 37 mm in women [35], measured in M mode.
4. Maximum pulmonic valve gradient < 30 mmHg [29–31].
5. Mean aortic valve gradient < 20 mmHg [29–31].
6. Maximum left intraventricular gradient < 30 mmHg [37].
7. Normal or near normal right ventricular (RV) systolic function defined as:
 - a. RV basal four-chamber end-diastolic diameter < 42 mm [39] or RV diameter < 41 mm in the long-axis parasternal view [36];
 - b. RV fractional area change > 35% [35,36,39];
 - c. tricuspid annular plane systolic excursion > 16 mm or S' wave > 10 cm/s or both [36,39,40];
 - d. the RV ejection fraction is a challenging measurement in routine practice, which has not been widely validated clinically [39]. Because of the heterogeneity of all other methods, echocardiographic three-dimensional volumetric measurement is recommended [39]; it is considered normal when its value is > 45% [41]. The RV ejection fraction is considered normal when > 50% by isotope or magnetic resonance imaging methods [42].
8. A normal mean pulmonary artery pressure at rest, defined as < 20 mmHg or, in the absence of haemodynamic measurement, as a maximum velocity of tricuspid regurgitation < 2.8 m/s [43].
9. Ascending aortic diameter < 45 mm [9,44].

Results required on exercise testing

- Absence of functional symptoms during the test, including angina pectoris, syncope, fainting and palpitation.
- Maximum functional capacity > 8 MET and first ventilatory threshold > 4 MET.
- Normal adaptation of the systemic systolic blood pressure to exercise, defined as an increase of > 20 mmHg.
- Absence of major supraventricular or ventricular arrhythmia.
- Absence of prolonged asystole.
- Absence of major change in repolarisation.
- Transcutaneous oxygen arterial saturation > 95% at rest and during exercise.

Results required on 24-h ambulatory electrocardiogram

Absence of prolonged asystole or major arrhythmia at rest or during exercise and < 500 isolated ventricular extrasystoles/24 h at rest. In case of arrhythmias or conduction abnormalities, the recommendations published by the FFESSM are applicable [45].

Exceptional decisions in cases of intracardiac shunts

If, based on all measurable criteria, an applicant is eligible, a patent ductus arteriosus is not a contraindication as the shunt is exclusively left-to-right and cannot be reversed by the variations in intrathoracic pressure. However, interatrial shunts are a contraindication; despite being left-to-right shunts, they may be reversed by increases in intrathoracic pressure, and enable the passage of large bubbles into the arterial circulation in a desaturation phase. With regard to patent foramen ovale, which is not strictly speaking a CHD, the readers are referred to the relevant recommendations formulated by the FFESSM [46].

Exceptions related to pacemakers and implantable cardioverter defibrillators

Although state-of-the-art devices are highly pressure resistant, it seems prudent to limit the dive to a depth of 30 m, unless specifically mentioned by the manufacturer [47]. The mere presence of a pacemaker is not a contraindication to diving, and the ultimate decision hinges on an overall evaluation [45].

The implant of a cardioverter defibrillator is an absolute contraindication to scuba diving. While these devices effectively prevent sudden death, they do not prevent syncope, hence the risk of drowning.

Conclusions

This document was originally written to allow scuba diving under certain circumstances, for patients in whom this activity used to be formally contraindicated; this is based on fragile and debatable scientific data. Therefore, we are offering this tool to help in the decision-making and to enable individual evaluations. In order to be as practical and flexible as possible, we wrote these recommendations as a guide, leaving users a certain degree of decisional freedom; they need to confirm the eligibility of the applicants, take their behavioural disposition in consideration and openly discuss the possible restrictions that they might impose. Authorization and the modalities of practicing recreational diving must be renewed yearly.

The organization of a longitudinal registry of authorized recreational scuba divers would allow a prospective follow-up of these patients, leading to validation and perhaps evolution of the recommendations made.

Disclosure of interest

The authors declare that they have no competing interest.

References

- [1] FFESSM. Contre-indications médicales pour plonger; 2012 http://www.ffessm.fr/recherche_detail.asp?numero=19&origine=FAQ.
- [2] Warnes CA, Liberthson R, Danielson GK, et al. Task force 1: the changing profile of congenital heart disease in adult life. *J Am Coll Cardiol* 2001;37:1170–5.
- [3] Marelli AJ, Ionescu-Ittu R, Mackie AS, Guo L, Dendukuri N, Kaouache M. Lifetime prevalence of congenital heart disease in the general population from 2000 to 2010. *Circulation* 2014;130:749–56.
- [4] Marelli AJ, Mackie AS, Ionescu-Ittu R, Rahme E, Pilote L. Congenital heart disease in the general population: changing prevalence and age distribution. *Circulation* 2007;115:163–72.
- [5] Fredriksen PM, Kahrs N, Blaasvaer S, et al. Effect of physical training in children and adolescents with congenital heart disease. *Cardiol Young* 2000;10:107–14.
- [6] Hirth A, Reybrouck T, Bjarnason-Wehrens B, Lawrenz W, Hoffmann A. Recommendations for participation in competitive and leisure sports in patients with congenital heart disease: a consensus document. *Eur J Cardiovasc Prev Rehabil* 2006;13:293–9.
- [7] FFESSM, CMPN. Manuel du Médecin Fédéral; 2013 <http://medical.ffessm.fr/wp-content/uploads/MANUEL-DU-MEDECIN-FEDERAL-FFESSM-CMPN-AU-28-11-2013.pdf>.
- [8] Houyel L, Khoshnood B, Anderson RH, et al. Population-based evaluation of a suggested anatomic and clinical classification of congenital heart defects based on the International Paediatric and Congenital Cardiac Code. *Orphanet J Rare Dis* 2011;6:64.
- [9] Budts W, Borjesson M, Chessa M, et al. Physical activity in adolescents and adults with congenital heart defects: individualized exercise prescription. *Eur Heart J* 2013;34:3669–74.
- [10] Giannakoulas G, Dimopoulos K. Exercise training in congenital heart disease: should we follow the heart failure paradigm? *Int J Cardiol* 2010;138:109–11.
- [11] CTN de la FFESSM. Le Manuel de Formation Technique; 2014 http://www.ffessm.fr/gestionenligne/manuel/44-Introduction_MFT.pdf.
- [12] FFESSM. Certificat médical de non contre-indication à la pratique des activités subaquatiques. Available at: <http://medical.ffessm.fr/wp-content/uploads/CMPN.Certif-modifi-retour-copie.pdf>.
- [13] Boussuges A, Blanc F, Carturan D. Hemodynamic changes induced by recreational scuba diving. *Chest* 2006;129:1337–43.
- [14] Boussuges A, Regnard J. Physiologie cardiovasculaire et bilan hydrominéral. In: Broussolle B, Méliet JL, Coulange M, editors. *Physiologie et Médecine de la plongée*. Paris: Ellipses; 2006. p. 115–39.
- [15] Peacher DF, Martina SD, Otteni CE, Wester TE, Potter JF, Moon RE. Immersion pulmonary edema and comorbidities: case series and updated review. *Med Sci Sports Exerc* 2015;47:1128–34.
- [16] Wester TE, Cherry AD, Pollock NW, et al. Effects of head and body cooling on hemodynamics during immersed prone exercise at 1 ATA. *J Appl Physiol* 2009;106:691–700.
- [17] Keatinge WR, Evans M. The respiratory and cardiovascular response to immersion in cold and warm water. *Q J Exp Physiol Cogn Med Sci* 1961;46:83–94.
- [18] Marabotti C, Chiesa F, Scalzini A, et al. Cardiac and humoral changes induced by recreational scuba diving. *Undersea Hyperb Med* 1999;26:151–8.

- [19] Jette M, Sidney K, Blumchen G. Metabolic equivalents (METs) in exercise testing, exercise prescription, and evaluation of functional capacity. *Clin Cardiol* 1990;13:555–65.
- [20] Bove AA. The cardiovascular system and diving risk. *Undersea Hyperb Med* 2011;38:261–9.
- [21] Mitchell SJ, Bove AA. Medical screening of recreational divers for cardiovascular disease: consensus discussion at the Diverse Alert Network Fatality Workshop. *Undersea Hyperb Med* 2011;38:289–96.
- [22] Pollock NW. Aerobic fitness and underwater diving. *Div Hyperbaric Med* 2007;37:118–24.
- [23] Ainsworth BE, Haskell WL, Herrmann SD, et al. The Compendium of Physical Activities Tracking Guide. Healthy Lifestyles Research Center, College of Nursing & Health Innovation. Arizona State University; 2011 <https://sites.google.com/site/compendiumofphysicalactivities/home>.
- [24] American Thoracic Society, American College of Chest Physicians. ATS/ACCP Statement on cardiopulmonary exercise testing. *Am J Respir Crit Care Med* 2003;167:211–77.
- [25] Baron B, Noakes TD, Dekerte J, et al. Why does exercise terminate at the maximal lactate steady state intensity? *Br J Sports Med* 2008;42:828–33.
- [26] Thaulow E, Fredriksen PM. Exercise and training in adults with congenital heart disease. *Int J Cardiol* 2004;97(Suppl. 1):35–8.
- [27] Dua JS, Cooper AR, Fox KR, Graham Stuart A. Exercise training in adults with congenital heart disease: feasibility and benefits. *Int J Cardiol* 2010;138:196–205.
- [28] Maron BJ, Chaitman BR, Ackerman MJ, et al. Recommendations for physical activity and recreational sports participation for young patients with genetic cardiovascular diseases. *Circulation* 2004;109:2807–16.
- [29] Graham Jr TP, Driscoll DJ, Gersony WM, Newburger JW, Rocchini A, Towbin JA. Task Force 2: congenital heart disease. *J Am Coll Cardiol* 2005;45:1326–33.
- [30] Pelliccia A, Fagard R, Bjornstad HH, et al. Recommendations for competitive sports participation in athletes with cardiovascular disease: a consensus document from the Study Group of Sports Cardiology of the Working Group of Cardiac Rehabilitation and Exercise Physiology and the Working Group of Myocardial and Pericardial Diseases of the European Society of Cardiology. *Eur Heart J* 2005;26:1422–45.
- [31] Takken T, Giardini A, Reybrouck T, et al. Recommendations for physical activity, recreation sport, and exercise training in paediatric patients with congenital heart disease: a report from the Exercise, Basic & Translational Research Section of the European Association of Cardiovascular Prevention and Rehabilitation, the European Congenital Heart and Lung Exercise Group, and the Association for European Paediatric Cardiology. *Eur J Prev Cardiol* 2012;19:1034–65.
- [32] Meehan C, Bennett M. Medical assessment of fitness to dive - comparing a questionnaire and a medical interview-based approach. *Diving Hyperb Med* 2010;40:119–24.
- [33] SFMES. Sample questionnaire for evaluation of cardiovascular status. Available at: http://www.sfm.es.org/images/sfm.es/pdf/Visite_NCI.pdf.
- [34] Kempny A, Dimopoulos K, Uebing A, et al. Reference values for exercise limitations among adults with congenital heart disease. Relation to activities of daily life—single centre experience and review of published data. *Eur Heart J* 2012;33:1386–96.
- [35] Kou S, Caballero L, Dulgheru R, et al. Echocardiographic reference ranges for normal cardiac chamber size: results from the NORRE study. *Eur Heart J Cardiovasc Imaging* 2014;15:680–90.
- [36] Lang RM, Badano LP, Mor-Avi V, et al. Recommendations for cardiac chamber quantification by echocardiography in adults: an update from the American Society of Echocardiography and the European Association of Cardiovascular Imaging. *J Am Soc Echocardiogr* 2015;28:1–39 [e14].
- [37] Elliott PM, Anastakis A, Borger MA, et al. 2014 ESC Guidelines on diagnosis and management of hypertrophic cardiomyopathy: the Task Force for the Diagnosis and Management of Hypertrophic Cardiomyopathy of the European Society of Cardiology (ESC). *Eur Heart J* 2014;35:2733–79.
- [38] Kampmann C, Wiethoff CM, Wenzel A, et al. Normal values of M mode echocardiographic measurements of more than 2000 healthy infants and children in central Europe. *Heart* 2000;83:667–72.
- [39] Rudski LG, Lai WW, Afilalo J, et al. Guidelines for the echocardiographic assessment of the right heart in adults: a report from the American Society of Echocardiography endorsed by the European Association of Echocardiography, a registered branch of the European Society of Cardiology, and the Canadian Society of Echocardiography. *J Am Soc Echocardiogr* 2010;23:685–713 [quiz 86–88].
- [40] Abergel E, Bernard Y, Brochet E, et al. Update of the French Society of Cardiology recommendations on indications for Doppler echocardiography published in 1999. *Arch Cardiovasc Dis* 2008;101:249–89.
- [41] Tamborini G, Marsan NA, Gripari P, et al. Reference values for right ventricular volumes and ejection fraction with real-time three-dimensional echocardiography: evaluation in a large series of normal subjects. *J Am Soc Echocardiogr* 2010;23:109–15.
- [42] Maceira AM, Prasad SK, Khan M, Pennell DJ. Reference right ventricular systolic and diastolic function normalized to age, gender and body surface area from steady-state free precession cardiovascular magnetic resonance. *Eur Heart J* 2006;27:2879–88.
- [43] Galie N, Hoeper MM, Humbert M, et al. Guidelines for the diagnosis and treatment of pulmonary hypertension: the Task Force for the Diagnosis and Treatment of Pulmonary Hypertension of the European Society of Cardiology (ESC) and the European Respiratory Society (ERS), endorsed by the International Society of Heart and Lung Transplantation (ISHLT). *Eur Heart J* 2009;30:2493–537.
- [44] Hiratzka LF, Bakris GL, Beckman JA, et al. 2010 ACCF/AHA/AATS/ACR/ASA/SCA/SCAI/SIR/STS/SVM guidelines for the diagnosis and management of patients with Thoracic Aortic Disease: a report of the American College of Cardiology Foundation/American Heart Association Task Force on Practice Guidelines, American Association for Thoracic Surgery, American College of Radiology, American Stroke Association, Society of Cardiovascular Anesthesiologists, Society for Cardiovascular Angiography and Interventions, Society of Interventional Radiology, Society of Thoracic Surgeons, and Society for Vascular Medicine. *Circulation* 2010;121:e266–369.
- [45] Brounat B, Houriez P, Lafay V, Roche F, Finet G, Grandjean B. Pratique de la plongée et des sports subaquatiques par les patients présentant des troubles de la conduction ou du rythme cardiaque : Recommandations pour la FFESSM. *Bull Medsubhyp* 2009;19:177–84.
- [46] FFESSM. Annexe 3-2-1e1 : Conseil aux médecins prescripteurs. Available at: http://medical.ffessm.fr/wp-content/uploads/RI_medical_annexe3_2_1e1-1.pdf.
- [47] Lafay V, Trigano JA, Gardette B, Micoli C, Carre F. Effects of hyperbaric exposures on cardiac pacemakers. *Br J Sports Med* 2008;42:212–6.