The Cardiovascular System and Diving Risk*

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Recreational scuba diving is a sport that requires a certain physical capacity in addition to consideration of the environmental stresses produced by increased pressure, low temperature and inert gas kinetics in tissues of the body. Factors that may influence ability to dive safely include age, physical conditioning, tolerance of cold, ability to compensate for central fluid shifts induced by water immersion and ability to manage exercise demands when heart disease might compromise exercise capacity. Patients with coronary heart disease, valvular heart disease, congenital heart disease and cardiac arrhythmias are capable of diving, but consideration must be given to the environmental factors that might interact with the cardiac disorder. Understanding of the interaction of the diving environment with various cardiac disorders is essential to providing a safe diving environment to individual divers with known heart disease.

The Diving Environment and the Cardiovascular System
Recreational scuba diving is a popular sport that had its beginnings in the early 1950s. It has grown over the past 60 years into a well-established recreational sport that involves an estimated 3 million divers in the United States. Besides recreational applications, diving has been an active commercial occupation for more than 100 years and is an important component of marine activity in the U.S. Navy and other navies around the world. Special training for physicians through academic and military programs has led to an identified specialty (American Board of Preventive Medicine 2010). While both commercial and military diving have physicians trained and committed to supporting their operations, recreational divers often present themselves to community physicians who are not experts in this area of medicine. Because of the high prevalence of cardiovascular disease (CVD) in our population, many recreational divers or potential divers seek advice from physicians regarding their ability to dive with various cardiovascular disorders.

To understand the interaction of the patient with cardiovascular system disease and the diving environment, it is important to elucidate the various stress factors that relate to this environment. Divers with CVD are particularly prone to complications of their disorders when there are excess physical exercise demands, when environmental factors result in increased blood pressure or when stresses result in increased sympathetic activation that can aggravate ischemia or induce abnormal and potentially harmful cardiac arrhythmias. In addition, the unique environment of water immersion adds thermal stress — usually cold stress — and the well-documented shifts of blood centrally (Arborelius et al. 1972) that can result in enough acute volume overload to a compromised heart to result in acute decompensated heart failure. Several diving-related disorders (lung barotrauma and arterial gas embolism, immersion pulmonary edema) are known to produce fatalities due to direct compromise of cardiac function or hypoxemia induced by pulmonary edema.

These are well known in the diving community, and specific precautions are provided to divers to help avoid their occurrence.

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Population Demographics
The recreational diving community in the United States is heterogenous, involving male and female divers ranging in age from 8 to 60-plus years old (Denoble, Caruso et al. 2008). The current practice of providing lifelong certification means that once certified, a diver can have a diving experience spanning many decades with no obligation to evaluate state of health or illness as it relates to diving. Many divers continue diving into their seventh and eighth decades. This aging population of divers has found means to control adverse environments to fit their capacity for safe diving in light of reduced physical capacity due to aging or chronic illness. Despite these precautions, data from the DAN insurance population (Denoble, Caruso et al. 2008) indicates that increased age is associated with a higher diving-related mortality from both cardiac and other causes. Figure 1 shows the distribution of cardiology-related health questions that were submitted by divers to a public dive medicine website (www.scubamed.com) and were answered directly by the author (AAB). All these cardiac disorders can result in a diving fatality related to heart disease based on the severity of the illness, co-morbidities and the environmental stress experienced during diving.

Figure 1: Cardiac-related queries to the website www.scubamed.com

Note: Total queries over nine years were 750; 156 were related to cardiovascular disease. CABG – coronary artery bypass surgery; CHD – congenital heart disease; HF – heart failure; HTN – hypertension; ICD – implanted cardioverter-defibrillator; IPE – immersion pulmonary edema; PCI – percutaneous coronary intervention; PFO – patent foramen ovale; TX – heart transplant; VHD – valvular heart disease

Physical Work Demands
The studies of Pendergast et al. (1996, 2003) documented the oxygen demands of swimming with scuba gear at various speeds. Of note is the nonlinear relation between swimming speed and work demand due to the well-known second-order relation between drag energy and velocity in water (Batchelor 1967). Pendergast et al. provided equations that would allow estimates of oxygen consumption at increasing swimming speeds (Figure 2).
The demands for swimming ability for safe diving are controversial. In most environments, diving exercise demand is not likely to exceed 15-20 feet/minute swimming speed and for recreational diving may reach speeds of only 4-5 feet/minute. However, in situations where current or distance is involved, demand could reach 100 feet/minute (about 1 knot). For a diver to manage usual contingencies (current of 0.4-0.5 knots), wind or surface action, oxygen consumption (VO$_2$) demands during diving can reach levels of 20 ml/kg/minute (6-7 metabolic equivalents or METs (U.S. Navy 2008)). The “maximal steady state” is a workload of about 50 percent of maximal oxygen consumption (Levine 2001; Baron et al. 2008) that allows continuous exercise without excess ventilation and without a progressively increasing blood lactate (Faude et al. 2009). This state can be sustained for 50-60 minutes, while exercise at 60-70 percent of maximal oxygen consumption in an average-conditioned diver cannot be sustained for more than 15-20 minutes (Lepretre et al. 2008). Thus a diver with a steady state exercise capacity of 6-7 METs can expect to manage most diving contingencies without concern for cardiovascular complications.

In most occupational exposures requiring increased physical activity, guidelines recommend maintaining workloads below 50 percent of maximal oxygen consumption (Levine 2001). Based on this relationship, a diver who is expected to minimize safety concerns related to environmental contingencies should have a maximum oxygen consumption of 12-13 METs. Divers with a peak exercise capacity below that level could expect to dive safely in low-stress conditions (i.e., warm water, minimal currents, minimal surface action) but could develop some evidence of cardiovascular limitations under stressful diving conditions. This is likely to be manifested as a high ventilation rate with the sensation of dyspnea while breathing through a mouthpiece — a situation that can induce a panic reaction. Very young, older or less well-conditioned divers and those with cardiovascular disorders that limit exercise capacity must develop plans that provide them support (e.g., buddy system) when diving conditions are expected to be adverse or plan diving in conditions where the likelihood of a high stress load is minimal.

**Thermal Stress**

Most divers are immersed in water below skin temperature and therefore lose body heat during their exposure. In this environment, thermal conduction and
convection are the major pathways for heat loss, and minimizing surrounding water contact with the skin is the usual means of protection. The U.S. Navy has prescribed the methods for thermal protection of divers in different water temperatures (U.S. Navy 2008). In diving where water temperature is below 50°F, for prolonged exposures hot water is circulated to the diver's suit to maintain thermal stability. Recreational divers are exposed to a wide range of water temperatures. Diving in northern-hemisphere seas and lakes where water temperature may be 50°F requires special dive suit protection. However, even when diving in tropical regions where water temperature is 80°F, conductive and convective heat loss will occur without proper thermal protection.

Although the cardiac effects of extreme hypothermia are well described (Tipton et al. 2004), this situation is rare in recreational diving, and the more likely scenario involves the effect of moderately reduced body temperature on the heart and circulation. A reduced body temperature induces vasoconstriction in skin and skeletal muscle, with increased systemic resistance and increased blood pressure (Tipton et al. 2004). In individuals with coronary disease this reaction can induce myocardial ischemia with subsequent angina or ischemia-induced arrhythmias.

Immersion

When an individual is immersed in water to the neck, the pressure effects on the venous system result in a shift of 600-700 ml of blood centrally (Arborelius et al. 1972). This shift is managed in the normal heart by the well-described Starling mechanism (Sarnoff et al. 1960), but in a compromised left ventricle this amount of volume shift can result in acute heart failure. We have encountered a number of divers with reduced ejection fraction who developed acute pulmonary edema while diving or snorkeling. In addition to acute heart failure known to occur in patients with compromised left ventricular function, some divers with normal left ventricular function appear to be susceptible to a clinical syndrome similar to acute heart failure.

This phenomenon has been described as immersion pulmonary edema (IPE), and presently its cause has not been identified (Slade et al. 2001; Wilmshurst et al. 1989). Possible causes of IPE include negative airway pressure due to high inspiratory resistance. This phenomenon, called negative-pressure pulmonary edema, has been described in anesthesia procedures (Bove 2004). Recent data also suggest that impairment of left ventricular relaxation can be involved in pulmonary edema by causing elevation of left ventricular end diastolic pressure during exercise and subsequent pulmonary venous hypertension (Kato et al. 2008). In most cases of immersion pulmonary edema, cardiac function is found to be normal (Slade et al. 2001).

Review of cardiovascular conditions relevant to diving

Congenital heart disease

The younger population (ages 9-35) is most likely to have cardiovascular-related disorders due to congenital heart disease. These can include surgically corrected complex congenital heart disease, channelopathies that risk sudden death and conduction abnormalities that can compromise normal heart function. Although a patent foramen ovale is congenital in origin, it does not contribute to risk for sudden death while diving.

Congenital heart disease encompasses a wide range of heart abnormalities, but the focus here is on the disorders that risk sudden death while diving. These include congenital aortic stenosis or insufficiency; aortic coarctation; and Marfans.
Both acquired and congenital abnormalities can threaten safety when diving.

Surgically corrected complex congenital heart disease
Survival of children with complex congenital heart disease has improved over the past 30 years primarily due to improved surgical methods for correcting the abnormalities. The population of adults with congenital heart disease is increasing, and many of these adults are well enough compensated with regard to their cardiac performance that they seek medical advice for sport diving. Usual diagnoses include Tetralogy of Fallot, pulmonary or right ventricular atresia and transposition of the great vessels. Surgical correction for Tetralogy of Fallot leaves the subject with adequate exercise tolerance for diving but at risk for serious arrhythmias or sudden death (Vignati et al. 1998; Silka et al. 1998). Evaluation of these candidates for diving requires careful communication with the cardiologist in charge of their long-term care. Correction of transposition often leaves the right ventricle (RV) as the systemic ventricle. The RV often fails in the third or fourth decade of life due to the chronic mismatch of load (Szymański et al. 2009), and the patient may require heart transplantation. These patients with poor tolerance to central fluid shifts can develop acute heart failure when immersed to the neck. In general, exercise tolerance is limited. However, isolated incidences of low-stress diving have been completed successfully in these patients. Counseling about risk is essential in these patients if they plan to dive.

Patients with Fontan shunts from the right atrium to the pulmonary artery do not have a functioning right ventricle and are highly dependent on right-atrial pressure being maintained to a very close tolerance (Gewillig et al. 2010). They may develop acute heart failure from central fluid shifts, or they may develop a low cardiac output syndrome from even mild degrees of dehydration. Either situation can quickly degenerate into a lethal outcome. Patients with Fontan shunts have been advised to swim for exercise. However, the same fluid shift situation occurs in swimming, so those who can tolerate swimming should be able to tolerate low-stress diving safely.

Rhythm and conduction abnormalities
Both acquired and congenital abnormalities can threaten safety when diving. Dangerous acquired arrhythmias include ventricular tachycardia, often related to ischemia or cardiomyopathy and atrial fibrillation, or flutter with uncontrolled heart rate. Screening for these abnormalities should include careful physical examination of the heart and an electrocardiogram to document abnormal rhythms noted on examination. When there is concern for risk of a dangerous arrhythmia, continuous ECG monitoring, particularly during exercise, can also provide an assessment of risk.
**Long QT syndrome**

The work of Ackerman et al. (1999) demonstrated a form of the long QT syndrome that resulted in risk of sudden death when swimming or water-immersed. This effect was detected in a series of individuals who drowned. Clinical detection of the long QT syndrome is by electrocardiography, but most diving candidates do not have an electrocardiogram as a part of diving clearance. Because of the rarity of this disorder, routine screening of recreational diving candidates with an ECG is costly and impractical. In subjects with the long QT syndrome, the family history may be positive for sudden death in young family members. It is therefore important for screening to inquire about family history of sudden death in young family members, particularly in females, who are more prone to the syndrome. The channel abnormality in long QT triggers a particular form of ventricular tachycardia called torsades des pointes (Figure 3) that degenerates into ventricular fibrillation (Kaufman 2009).

![Figure 3: ECG showing torsades des pointes](http://archive.rubicon-foundation.org)

**Wolf-Parkinson-White Syndrome**

An important congenital conduction defect that can cause sudden death is the Wolf-Parkinson-White (WPW) syndrome. This syndrome is the result of an accessory conduction fiber that crosses the atrioventricular (AV) ring and allows direct conduction of atrial impulses to the ventricle without delay through the AV node. A characteristic ECG pattern is noted (Figure 4). Patients with this accessory pathway have a history of palpitations and may develop rapid supraventricular tachycardias that can deteriorate into ventricular fibrillation. This disorder is readily cured by ablation of the accessory bundle, and individuals with normal conduction post-ablation are not prone to complications. A history of palpitations should trigger further inquiry and an ECG for evaluation. As noted previously, routine ECG screening of sport diving candidates would be impractical.

![Figure 4: ECG showing WPW syndrome pattern](http://archive.rubicon-foundation.org)

Note: The short P-R interval (see arrow) is due to pre-excitation.
Pacers and implanted cardioverter defibrillators
A pacer may be implanted for a number of indications, and most pacers are tested to depths of 80-130 feet (Lafay et al. 2008). Divers with pacemakers therefore will not damage the pacer at usual sport diving depths. However, the heart disorder that required an implanted pacer must be determined, as some disorders may put the diver at risk for a serious cardiac event. Cardioverter defibrillators (ICD) are implanted in patients at risk for lethal cardiac arrhythmias. Based on this indication, these patients are at risk for a serious arrhythmia while diving and subsequent firing of the ICD. This circumstance is likely to result in drowning, as the diver usually becomes disoriented either from the arrhythmia or from the ICD shock.

Heart failure and cardiomyopathy
Patients with significant reduction in left ventricular function (left ventricular ejection fraction (LVEF) < 35 percent) are at risk for exacerbation of heart failure while diving and development of the syndrome of acute decompensated heart failure (ADHF). This disorder, if untreated, will progress to severe metabolic derangement and death. As noted above, water immersion itself can provoke heart failure due to central blood shifts. Patients with severe reduction in LVEF (i.e., < 30 percent) are likely to note significant exercise impairment when diving. In general, safety considerations would prohibit diving with severe left ventricular dysfunction. However, a few divers have managed to perform short dives in low-stress conditions without developing ADHF. These patients are also prone to lethal arrhythmias, and many have implanted ICDs (see above). Patients with hypertrophic cardiomyopathy usually have normal systolic left ventricular function but are also prone to sudden death, and should be evaluated for risk during any form of exercise. A proportion of these patients have ICDs based on prior history or clinical assessment of sudden death risk.

Coronary disease
For divers older than age 35, the dominant risk for sudden death is from coronary disease. This disorder is the result of vascular injury and atherosclerosis that ultimately result in occlusion of a coronary artery, with sudden death in about one-third of patients who experience an acute myocardial infarction (AMI). Although the incidence of coronary disease death is falling (American Heart Association 2010), the rising incidence with age (Figure 5) makes this diagnosis...
the most important consideration when clearing divers above 35 years old. The analysis of cardiovascular-related deaths from the DAN database (Caruso et al. 2001) indicated that CVD fatalities peaked in the 50- to 60-year age range. Figure 6 shows the age distribution of diving deaths from cardiovascular disease. The reduced number of deaths in the older divers is likely due to the lower number of divers above 60 years old. The data of Denoble, Pollock et al. (2008) indicates that age above 50 years and male sex are the principal predictors of cardiovascular death while diving. The relation between sudden cardiac death and exercise is well accepted (Mittleman et al. 1993; Willich et al. 1993). The common scenario is a male over age 40 with occult coronary disease, who is subjected to a high exercise stress, develops symptomatic ischemia, myocardial infarction or sudden death.

![Figure 6: Diving-related CV deaths reported to DAN](source: Caruso et al. 2001)

The exercise demands of recreational diving should be understood in this context, and for individuals suspected to be at risk for coronary disease, screening prior to diving is essential to prevent a lethal cardiovascular event.

Screening for coronary disease is based first on assessment of coronary disease risk factors (Table 1).

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<td>Age</td>
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<td>Blood pressure</td>
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Source: Wilson et al. 1998

A commonly used cardiovascular disease risk score is available from longitudinal studies in Framingham, Mass. (Wilson et al. 1998). The Framingham Risk Score defines the 10-year risk of developing cardiovascular disease: A risk score lower than 10 percent (i.e., less than 1 percent/year risk) is considered to be a low score. If a subject is assessed to be at low risk in general, that individual is not likely to have an acute coronary event while diving. On the other hand, high-risk
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individuals (Framingham score >20 percent) could be at considerable risk and should have further evaluation to evaluate whether diving will be safe.

Intermediate-risk individuals with a Framingham score between 10 percent and 20 percent should have further risk stratification to assess their risk for an acute coronary event while diving. There are several choices for defining risk in these individuals, but one method that should be incorporated is exercise stress testing, as the concern is for an adverse cardiac event during the exercise demands of diving. For most divers in need of risk assessment, an exercise stress test with ECG monitoring is adequate to identify concerns related to exercise activity. Added imaging (myocardial perfusion or echocardiography) can be used in selected cases to improve accuracy of the stress test. Other methods (biomarkers, coronary calcium scoring, CT angiography) can be used to assess population-based risk, but for an individual, assessment of individual risk under conditions of increased stress is best done by functional testing. Individuals who show ischemic changes during exercise, particularly if corroborated with a concurrent imaging result, are likely to be at increased risk during diving and should have further evaluation, and possibly intervention, before considering diving.

Patients with known coronary disease often have been subject to revascularization either by coronary bypass surgery or by percutaneous catheter intervention, currently with implantation of one or more stents in the affected coronary arteries. The degree of revascularization can determine safety in diving. With complete revascularization, low-stress diving can be accomplished successfully, but diving in rough seas, fast currents or cold water would be risky. There are many divers who have returned to diving after either coronary bypass surgery or stenting. Success in return to diving is based on restored exercise capacity without ischemia after revascularization and choosing diving environments that do not produce excess stress on the cardiovascular system.

Conclusions
Cardiovascular disease is the third most common cause of death while diving (Denoble, Caruso et al. 2008; Divers Alert Network 2004) and remains the principal cause of death in the general population (National Institutes of Health 2011). While the majority of cardiac disorders are compatible with safe diving, in divers with cardiovascular disease consideration of the stress created by adverse diving environments must be considered. There are several unique situations that involve central blood shifts due to water immersion, arrhythmias induced by the aquatic environment and increased exercise demands caused by an adverse diving environment that must be considered in individuals with heart disease. Inappropriate exposure in an individual with heart disease can lead to a diving fatality. Collaboration between dive physicians and cardiologists caring for patients with complex cardiac disorders can often resolve risks and determine the safety of diving for individuals with cardiovascular disorders.

References


