Naval Submarine Medical Research Laboratory

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An Overview of the Unique Field of Submarine Medicine

LT Luke A. Beardslee, M.D., Ph.D.
Ben D. Lawson, Ph.D.
CAPT David P. Regis M.D.

Approved and Released by:
K. L. LEFEBRVE, CAPT, MSC, USN
Commanding Officer
NAVSUBMEDRSCHLAB

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The environment aboard a submarine presents unique challenges to ensuring Sailor mental and physical health, safety, and readiness. The crew works long hours under high stress, with limited access to fresh air, fresh food, sunlight, privacy, exercise, and communication with the outside world. Crew members are cared for by a single submarine Independent Duty Corpsman. No textbook and few reviews have been dedicated to submarine medicine. This report provides an overview of the health concerns and medical care challenges in the submarine environment, and discusses what can be done to ensure health and readiness while underway.

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Abstract
This is a brief review of the unique field of submarine medicine. We compare and contrast this field with other specialized areas of medicine, and describe some of the key concerns of the field.

The medical and social environment aboard a submarine is unlike any other that is routinely encountered. The crew, consisting of 120 or more individuals, is routinely housed in a highly confined space for extended periods of time. A submarine crew may traverse remote or disputed areas of the ocean far from rescue assets. Crew members work long hours under high stress, with limited access to fresh air, fresh food, sunlight, privacy, exercise, and communication with the outside world. During their voyage, crew members receive medical care from a single submarine Independent Duty Corpsman with limited assets.

These circumstances have led to the development of the unique field of submarine medicine, which addresses the mental and physical health, safety, and readiness of submariners. In addition to the aforementioned imperatives, the crew must be vigilant concerning the hazards of contact with hostile forces, onboard fires, anomalies in the breathing atmosphere (due to CO_2 or contaminant buildup), leaks or pressure hazards, undersea collision, or radiation exposure. If any of these hazards or stressors results in casualties, the Independent Duty Corpsman and shore-based medical personnel must be ready to provide effective aid. Nevertheless, no textbook and few reviews have been dedicated to submarine medicine. This report addresses this gap by providing an overview of the ways submarine medicine protects the health and readiness of submariners.

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Contents

Abstract iii

Acknowledgements iv

Table of Figures vi

1 Introduction 1

2 Similarities and Differences Between Submarine Medicine and Other Comparable Branches of Specialized Medicine 2

3 Submarine Medical Care and Resources 4

4 Overview of Submarine Medical Concerns 10

4.1 Core Health Concerns: Preventative Care and Occupational Health 10

4.1.1 Special Duty Screening for Submarine Duty 11

4.1.2 Mental Health 12

4.1.3 Radiation Health 13

4.1.4 The Submarine Atmosphere 14

4.1.5 Health Promotion 15

4.1.6 The Submarine Environment and Human Performance 16

4.1.7 Long Term Health Effects of Submarine Service 17

4.1.8 Medical Considerations during Submarine Escape and Rescue 19

4.2 Some Submarine Health Concerns or Gaps Requiring Further Research 20

4.2.1 Improved Mental Health Screening 21

4.2.2 Mental Health Support 21

4.2.3 Submarine Escape and Rescue 21

4.2.4 Long Term Field Care 22

4.2.5 Fatigue Leading to Performance Degradation 22

4.2.6 Long Term Health Effects of Submarine Service/Improved Monitoring 22

5 Conclusions 23

List of Abbreviations 24

References 26

Table of Figures

Figure 1. A U.S. Navy Los Angeles-class attack submarine 1
Figure 2. An IDC checks the heartbeat of a crew member. 3
Figure 3. Sample protocol for management of soft tissue infections 8

1 Introduction

The United States (U.S.) Navy submarine fleet consists of three types of nuclear-powered submarines with distinct missions: fast attack submarines, or SSNs (Ship, Submersible, Nuclear), SSBNs (Ship, Submersible, Ballistic, Nuclear), and SSGNs (Ship, Submersible, Guided, Nuclear). The fast attack submarines include the newer Virginia-class submarines and the older Los Angeles-class submarines. These boats are used for surveillance, launching of ordnance, transporting special operations forces, and anti-submarine warfare. The SSBNs are all Ohio-class submarines. They are larger than the fast attack boats and their main mission is to serve as sea-based nuclear deterrents. They are armed with Trident Missiles, which are capable of carrying nuclear payloads. The SSGNs are converted Ohio-class submarines meant to perform a variety of functions supporting combat operations in littoral waters including launching of special warfare operators from an onboard dry deck shelter. There also exists a subset of the SSNs, the SeaWolf-class of submarines, consisting of three boats that are used for special missions such as intelligence gathering and recovering objects from the ocean floor. While each type of submarine has a specific mission, all face similar challenges to the practice of medicine and maintenance of crew member health.

Figure 1. A U.S. Navy Los Angeles-class attack submarine. (Open source Navy photo from cpf.navy.mil, taken by Mass Communication Specialist 1st Class Jeffrey Price.)

U.S. submarines (Figure 1) perform a variety of missions and the duration that they can stay underwater on a mission is limited primarily by their food supply. The onboard reactor produces electricity that provides breathable air and potable water. One key to this prolonged underway capability is the submarine Independent Duty Corpsman (IDC). Each submarine takes a single IDC underway, whose responsibility is to monitor and maintain the crew's health throughout the voyage. In fact, the IDC is one of the few people on a submarine whose absence would prevent it from getting underway, due to the roles the IDC plays in providing medical care, preserving crew health, and managing occupational health surveillance programs. However, in the case of certain diving or dry dock operations, additional medical personnel may embark to deal with the complexities that can arise as a result of mission-specific factors.

In this report, we introduce the topic of submarine medicine and review the key considerations of the field. Submarine medicine has been developing since the birth of the Submarine Force near the start of the 20th century. Unlike other areas of medicine with unique considerations, our search of the literature discovered no published textbooks solely dedicated to submarine medicine, and few examples of review papers dedicated to the topic, none of which were more recent than the 1970s.[1-4] By comparison, aerospace medicine has at least three dedicated textbooks[5-7] and many published reviews. A medical practitioner serving the submarine community must exploit indirect resources derived from other areas of practice. For example, diving operations are often concomitant with submarine operations, and many full-length textbooks exist for diving medicine[8-11] (a field that will not be the focus of this report). However, these textbooks are not dedicated to submarine medicine and do not contain any chapters of more than a few pages that are specific to the topic. This document will fill a gap in the literature by giving an overview of the key topics that are unique to submarine medicine and are not already a part of general medical practice (i.e., topics that are not sufficiently covered already in a primary care or emergency medicine textbook).

2 Similarities and Differences Between Submarine Medicine and Other Comparable Branches of Specialized Medicine

The core constraints or considerations of submarine medicine are remoteness, operation in a hostile environment, limited resources, a self-contained atmosphere, lack of sunlight, and intentionally restricted communication with the outside world. These lead to challenges that are not seen in most other medical settings, even within the military. A submarine medical department consists of the submarine IDC, who is responsible for all daily medical care of the submarine crew (Figure 2) and for running the submarine's occupational health monitoring programs. Submarine IDCs must be able to care for a patient for three or more days using only the resources aboard the submarine, including medical supplies (stocked according to the Authorized Medical Allowance List (AMAL)) and any reference materials they have brought. Moreover, they must be able to do so while being prepared to treat many conditions that can arise in men and women between the ages of 18 and (approximately) 50.

Figure 2. An IDC checks the heartbeat of a crew member. (Open source Navy photo from dvidshub.net, taken by Mass Communication Specialist 1st Class Bill Larned).

Unique challenges aside, submarine medicine does have similarities to other areas of military medicine. For example, the U.S. Navy surface fleet also employs IDCs and operates in remote areas of the open ocean, where medical supplies and resources are limited. However, surface ships usually have more robust resources and the ability to maintain continual communication with the outside world. Some of the larger surface vessels have physicians aboard, and can medically evacuate (MEDEVAC) patients readily (e.g., via their organic air assets). Moreover, most surface ships are not nuclear-powered, which limits how far they can stray from resources such as fuel. Large vessels such as aircraft carriers and some amphibious ships have rich medical capabilities, including full operating rooms and a medical department of 50 or more people (including at least three board-certified physicians, two nurses, and several IDCs), with staffing augmentation as needed for specific missions. Large-deck amphibious ships may have extensive medical team expansion via fleet surgical teams capable of servicing multiple platforms in a task force.

Combat casualty care is a prominent subset of military medicine that requires specialized care outside of general medicine practices. Nevertheless, many of the problems seen in combat casualty care are distinct from the conditions encountered in submarine medicine. In combat casualty medicine, patients tend to be wounded and can decline rapidly from their injuries (e.g., due to exsanguination). While combat injuries tend to fall into a narrower range, they are often more acutely life or limb threatening.[12] This is in contrast to submarine medicine, where the injuries or illnesses are highly varied (ranging from industrial-type injuries to common illnesses) and usually less threatening (i.e., they take longer to develop and run their course). Also, rapid MEDEVAC to higher levels of care may not be as feasible in submarines.

Other specialized fields of medicine, such as *space* and *wilderness medicine*, have parallels with submarine medicine.[13-15] For example, astronauts must deal with comparable conditions of confinement, restricted communication with the outside world, difficulty of rescue, and limited resources, especially during extra-planetary travel. Confinement, in particular, creates a medical concern because the large number of individuals living in close proximity creates the potential to facilitate the spread of infections. Also, the submarine crew lives and works on the boat for 24 hours a day while underway, increasing the duration of exposure to occupational hazards such as noise and atmospheric contaminants. This prolonged exposure to the vessel environment is similar to that experienced by a spaceflight crew. Some contrasts between civilian space medicine and submarine medicine include the fewer number of potential patients in the space setting and the presence of fewer national security concerns hindering communications.

In *wilderness medicine*, care is similarly provided in a remote setting where resources are limited and prolonged field care may be necessary.[16] In contrast to wilderness medicine, however, the submarine IDC has access to equipment that likely would not be present in the wilderness setting where providers would be required to carry most of their medications and first aid gear. However, the submarine IDC must contend with the constant danger of individuals working around complex industrial or nuclear-power equipment in enclosed spaces, which could cause injuries not routinely encountered in wilderness medicine. For example, treatment of an industrial accident aboard a submarine, which might be relatively straightforward in an urban trauma center, becomes much more difficult in the isolated and sensitive environment of the submarine. Few other settings present the same level of isolation and resulting difficulty in treatment of industrial accidents. Examples of settings with some parallels include space vehicles and extractive industries in remote settings (i.e., mining or drilling for oil in the Arctic).

To summarize, submarine medicine has areas of similarity and difference with other areas of medical practice, such as combat casualty care, space medicine, and wilderness medicine. While the key medical areas of overlap have been identified, submarine medicine is unique in several ways. The key considerations that set submarine medicine apart are the combined influences of working in a remote operating environment (with unique stealth and combat hazards) and limited resources, restricted outside communication, difficulty of rapid medical evacuation, and the need to provide care for a wide range of conditions.

3 Submarine Medical Care and Resources

In contrast to some of the cases discussed above, a submarine's medical department consists of a single IDC. An IDC is an enlisted U.S. Navy Sailor who goes through basic training and then "A" school to become a hospital corpsman (medic). He or she is subsequently assigned to a variety of duties, which may include working as a technician in a hospital or clinic, time in the field with the Marines, or time on a ship. Usually, corpsmen of rank E-5, E-6, and E-7 are allowed to apply for the submarine IDC program. Once selected for the submarine IDC program, corpsmen complete a rigorous 16-month course at the Naval Undersea Medical Institute (NUMI) located in Groton, CT. The course includes a study of diseases affecting each organ system, radiation health, and the Basic Enlisted Submarine School (BESS). After completing their training, the IDCs are assigned to a submarine to begin practicing. Each year they are required to complete 25 hours of continuing education credits to maintain their credentials. Submarine IDCs are also required to maintain certification as Basic Life Support (BLS) and Advanced Cardiac Life Support (ACLS) instructors. These certifications allow IDCs to provide training and certification to other crew members in order to ensure adequate support in an emergency.

Submarine IDCs are supervised by undersea medical officers (UMOs). UMOs are stationed on land and generally do not serve aboard submarines with the IDC unless specific missions require it. UMOs serve as both supervisors to the IDC and as remote consultants. UMOs are physicians who have completed, at a minimum, four years of medical school and one year of graduate medical education training (PGY1/internship year). There are no requirements as to what type of internship training a UMO must complete. All UMOs must complete the 5-month undersea medical officer course offered at NUMI. This course includes submarine medicine, radiation health, diving medicine, and training as a Navy Diver (including 9-weeks at the Navy Dive Salvage Training Center). The majority of UMO billets are filled with first tour UMOs who usually have only completed an internship (the first year of residency after graduating from medical school). More senior-level UMO billets are usually filled by UMOs who have completed residency training and have attained board certification in their specialty

The IDC is considered an independent provider, practicing roughly at the level of a physician assistant or a nurse practitioner and is trained to deal with basic primary care and to provide stabilizing care in case of an emergency. The onboard medical resources available to the submarine IDC are sparse. The IDC's exam space aboard a Virginia-class submarine is small, roughly the size of a closet, while on a SSBN the space is somewhat larger and can accommodate a full exam table. Specific materials available to the IDC include intravenous (IV) antibiotics (a limited array is available onboard), IV narcotics, IV fluids, oxygen, oral medications, and tools to perform simple procedures such as abscess drainage and chest tube placement. To aid the IDC in providing care, the instruction that governs submarine IDC practice (CSLCSPINST 6000.2E) contains protocols for dealing with four conditions: nephrolithiasis, suicidal ideation, acute abdominal pain, and soft tissue infections.[17] The protocol for soft tissue infections is shown in Figure 3. These problems are of interest because they may be encountered underway but not require an immediate MEDEVAC, meaning that the IDC may have to treat the patient for an extended period. There are many other problems that the IDC may encounter, such as lacerations, sea sickness, gastrointestinal viruses, skin infections, rashes, or mental health issues.

Although medical equipment and resources are available, they are sparse compared to what would be found in a typical clinic. For example, laboratory testing capabilities to aid in diagnosis are limited to hematocrit level, urinalysis, fecal occult blood, and finger stick blood glucose.

The IDC faces many challenges not seen in civilian practice. One of the most prominent challenges is the isolation of the submarine environment, which limits access to outside medical advice or telehealth support. One line of effort dedicated to overcoming the challenges associated with isolation is the development of computer algorithms to assist with diagnosis and treatment. Several previous efforts have been devoted to developing such tools for use underway aboard submarines.[18] Even with computer-based assistance, some complicated cases will require additional input or medical advice. In these instances, the IDC can contact the UMO. IDCs needing to consult the UMO for treatment advice must send a medical advice message once it is feasible to do so and wait up to 24 hours for a response (see Appendix D of the CSLCSPINST 6000.2E for a sample med advice message).[17] The typical response times from the Force Medical Officer (a senior UMO and Type Commander (TYCOM) Surgeon at either COMSUBLANT or COMSUBPAC) is within a few hours, but operational requirements may prevent the submarine from being in position to receive the radio message immediately after it is sent. Until a response is received, the IDC must independently care for the patient.

The Force Medical Officer (FMO) will read the IDC's message and recommend further action, such as treatments that can be accomplished onboard and/or a MEDEVAC. Furthermore, if the FMO has received a MEDEVAC message from an IDC, the FMO will provide medical advice to the TYCOM Chief of Staff (the Submarine officer who is the second in command at either COMSUBLANT or COMSUBPAC) and the Commanding Officer of the Submarine where the patient is located. Specifically, the FMO will advise them on the necessity for MEDEVAC and the recommended MEDEVAC method. The mode of transportation for MEDEVAC is determined by considerations such as the sea state and the potential impact on the submarine's mission. Any MEDEVAC poses significant hazards, including the risk to rescue personnel who must venture far out into the ocean to meet the submarine, the hazard of moving a patient in narrow, confined spaces within the submarine, and the risk of injuries associated with moving the patient off of the deck of the submarine onto the rescue vehicle (e.g., falling overboard, crush injury).

Information available to the submarine IDC includes a variety of resources from the civilian world, with the caveat that such information must be accessible in book or CD form, as internet access is virtually non-existent while underway. This information includes the aforementioned (p. 5) protocols to follow for treating problems such as abdominal pain, skin/soft tissue infection, kidney stones, or mental health issues. Most submarine IDCs find a primary care-based reference that they prefer and can use as different medical conditions arise. To understand the medical assessments and treatments that are possible while underway, it is essential to know what medical supplies are available. There is a standard Authorized Medical Allowance List (AMAL) that describes the medications, equipment and supplies that should be available aboard submarines.[17] The AMAL includes items such as over-the-counter medications, antibiotics, narcotics, psychiatric medications, gauze/bandages, and minor procedure kits. Nevertheless, this list is limited versus what is available at a typical shore-based clinic.

There are several patient conditions that may require a MEDEVAC. It is best if these can be predicted and avoided before going underway. The Naval Submarine Medical Research Laboratory (NSMRL) has an Undersea Health Epidemiology Research Program (UHERP) to identify gaps in training/treatment options for the IDC or to identify additional screenings that may be needed to catch medical conditions before they manifest at sea. A report on MEDEVACs examining data from 2014 revealed that approximately 25% of all MEDEVACs were for psychiatric reasons, and another 21% of all MEDEVACs were due to injuries, with blunt trauma the most common mechanism.[19] Within the category MEDEVACs due to illness (rather than traumatic injury), approximately one-third were for psychiatric reasons, followed by approximately 13% for gastrointestinal illness/reasons.[19]

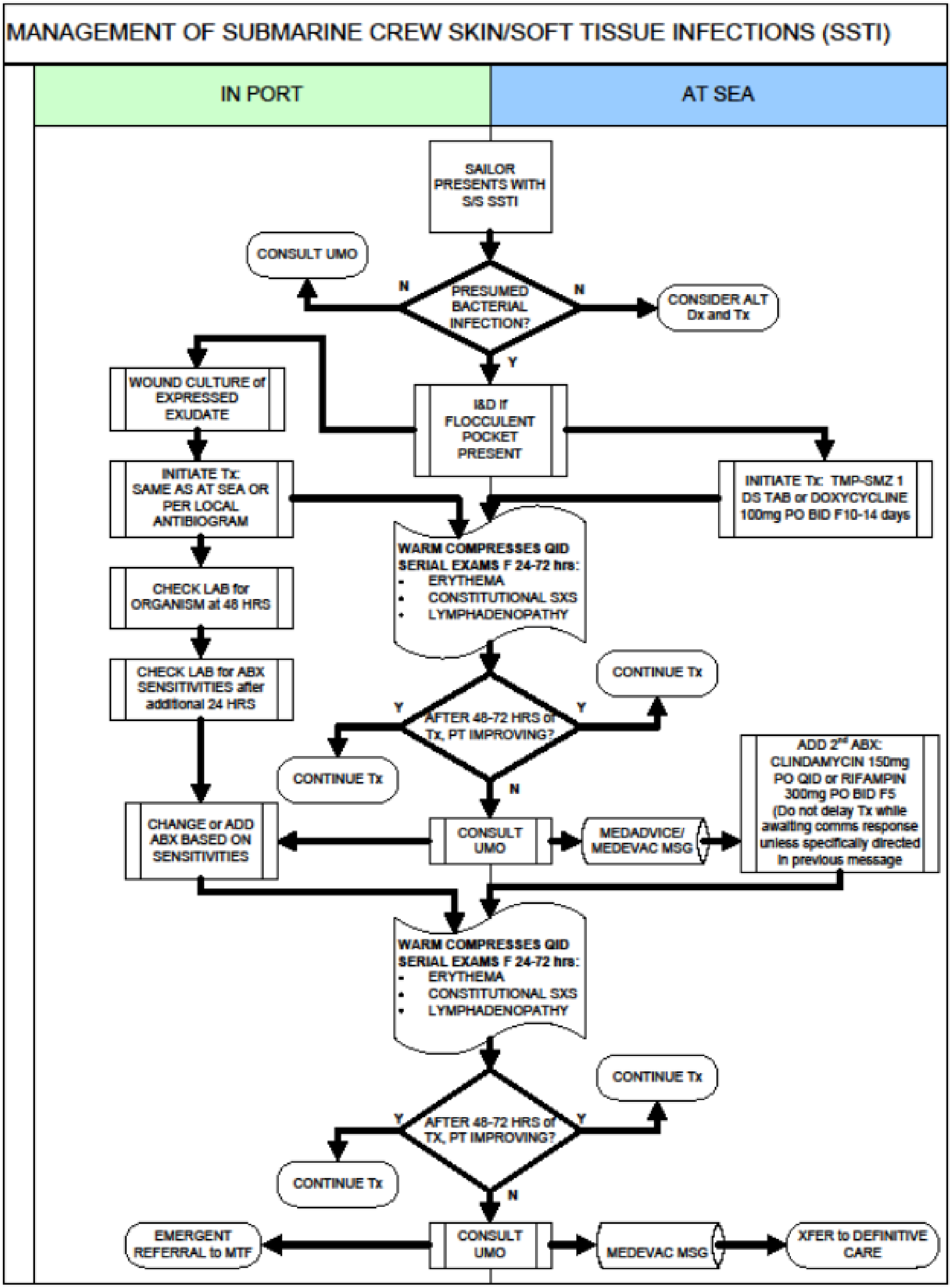

Figure 3. Sample protocol for management of soft tissue infections (CSLCSPINST 6000.2E).[17]

Below we list other studies that have examined health data from submariners while underway and documented the occurrence of illness and injury:

- One group of researchers looked at the prevalence of accidents that occurred during extended submarine patrols between 1997 to 1999.[20] They concluded that while common, accidents do not have a large detrimental effect on the submarine mission.[20]
- Another study described a database for cataloging health incidents aboard submarines for future analysis.[21]
- An older study looked at medical data from Polaris missile submarines over a ten-year period and documented a declining rate of respiratory illness following improvement to submarine atmospheric control.[22]
- More recent studies cataloged the most common types of health problems[23,24] and the medications used while underway.[25]
- Within the Royal Navy, reports have documented illness and injury from Vanguard-class Submarines,[26] and the medical experiences aboard Royal Navy Polaris submarines, including a report on surgical diseases presenting during Royal Navy Polaris patrols.[27,28]
- Additionally, around the time that the U.S. Navy was considering allowing women to serve aboard submarines, a technical report examined the potential medical needs of female submariners and how they could be met underway.[29]

Dental problems are another medical issue that IDCs can expect to encounter. One study that examined dental emergencies during submarine operations noted that out of 240 submarine patrols they studied, 109 emergency dental visits were recorded.[30] A case report from aboard a Royal Navy submarine in 1970 describes the repair of a fractured tooth using auto body resin, which attests to the resourcefulness required of submarine medical personnel[31]

One common medical issue is infection, which can occur in crew members as a result of the closed environment and close quarters. Though at least one study found lower infection rates among submariners as compared to surface Sailors,[22] an additional study of the prevalence of *Helicobacter pylori* infections in German submariners found elevated rates of infection compared to other military populations.[32]

There has been concern about the effect a reduced oxygen atmosphere aboard a submarine may have on soft tissue infections and wound healing. There is ample evidence to indicate that having the appropriate amount of oxygen is important for wound healing.[33-35] The reduced oxygen environment of the submarine (the acceptable oxygen range in the submarine atmosphere is 17-21%)[36] may have a detrimental effect on healing; however, not enough research has been conducted on wound healing under the ambient oxygen conditions found aboard submarines to prove or refute a causative link. Submarine IDCs anecdotally report increased wound healing times for abrasions. The submarine IDC medical manual[17] includes a soft tissue infection treatment protocol specifically to address these concerns (Figure 3).[a] One published article mentions that skin infections and disorders are of particular concern due to the artificial atmosphere and its effect on healing times, though no literature is cited to support this claim.[23] One observational study examined *Staphylococcus aureus* colonization in submariners and the potential link to soft tissue infections, but did not conclude that *Staphylococcus aureus* colonization was a major risk factor for skin health issues.[37] A second observational study aboard a U.S. SSBN found a pre-deployment *Staphylococcus aureus* colonization rate of 38.9%, which actually decreased over the course of a sample 3-month deployment. However, this study had some limitations including that it looked at a single crew and the participants represented a sample of convenience.[38]

While many illnesses have minimal effect on the ability of submariners to fulfill their duties and complete the mission,[23] the identification of conditions that repeatedly lead to MEDEVACs or impair a submariner's ability to function can help inform policy changes in terms of required screenings or additional medical resources (e.g., medications, equipment, treatment protocols) that should be available onboard submarines.

4 Overview of Submarine Medical Concerns

4.1 Core Health Concerns: Preventative Care and Occupational Health

Working aboard submarines requires continual awareness of safety, since radiation, pressurized air/steam/hydraulics, and many other potential hazards exist. Safety is an important part of preventative medicine aboard the submarine. Every precaution is taken to avoid injuries due to equipment. These precautions (e.g., turning off and marking electrical/mechanical components when maintenance is being performed, making sure chemicals are handled appropriately) are usually not the responsibility of the submarine IDC. Preventative safety measures often take the form of engineering controls such as tagging out circuit breakers and steams lines or other equipment in such a way that a safety barrier must be breached (e.g., a string or a piece of wire) to turn on a piece of equipment that is being repaired. The IDC is, however, responsible for testing enclosed spaces for hazardous gases before a person can enter them (also called gas free engineering). Similarly, the submarine IDC is responsible for testing the water supply of the boat (to ensure that it is not contaminated with bacteria) and serves in the role of a Radiation Health Officer tracking all crew members' exposures via the Thermoluminescent Dosimeter Program (TLD)

In submarine health research, emphasis has been placed on the care of the sick and injured as well as the MEDEVAC of casualties. These are important considerations and in-field care is

[a] In contrast, IDCs on surface ships go through different schooling and do not have a soft tissue protocol in the instruction that governs their practice (which would allow them to treat soft tissue infections without the direct supervision of a physician).

certainly a component of submarine medicine. The core considerations of submarine medicine, however, are preventative care and industrial hygiene. The components of these fields that are included within submarine medicine include health screening, mental health screening/support, radiation health, the submarine atmosphere, health promotion, the submarine environment and human performance, and the long-term health effects of living aboard submarines. These topics are discussed below.

4.1.1 Special Duty Screening for Submarine Duty

The health screening process for submariners begins with the special duty physical they undergo when they first volunteer for submarine duty. This complete history and full physical covers any past health conditions, ongoing issues, and current diagnoses. The physical includes examination of the eyes, ears, chest (including x-rays for candidates upon program entry), and abdomen, as well as a full neurological exam.[b] The physical is repeated every 5 years up until age 40, every 2 years until age 50, and annually after age 50.[39] The submarine special duty physical can be performed by any credentialed medical provider, but must be reviewed and signed by a UMO.

Section 15-106 of the Navy Manual of the Medical Department (MANMED) also contains an outline of the medical conditions that are disqualifying for submariners.[39] Submariners diagnosed with a medical condition are required to report it to the chain of command or to a healthcare provider (e.g., UMO or submarine IDC). The submarine physical is also intended to audit the medical records of the submariner to ensure that no conditions have been missed. A disqualifying condition does not mean that a submariner must be removed from service. In fact, many conditions merely require that a waiver be obtained for the submariner to stay on the boat. The process for submitting a waiver entails a review of the disqualifying condition, including the patient's initial presentation, response to treatment, and any requirements for ongoing care. Depending on the specific ailment, a clearance for duty from a specialist may be needed before a waiver will be considered (e.g., if a patient has a cardiac condition, a cardiologist may be required to state in writing that the Sailor is cleared for duty). The waiver package is completed by a UMO and includes (1) a Special SF600, which is a summary clinic note documenting the patient's course and recommends whether a waiver should be considered by the attending UMO, (2) clinic notes documenting the patient's diagnosis and treatment course (including any notes from specialists who evaluated the patient), (3) documentation that the patient has a current submarine physical, and (4) documentation of any imaging or other studies that the patient underwent as part of their evaluation and treatment. The waiver/disqualification is sent to the FMO / TYCOM Surgeon, for review and endorsement. The FMO will forward their recommendation to the Navy Bureau of Medicine (BUMED) for review, and BUMED will make a recommendation for or against approval, which they forward to the Navy Bureau of Personnel (BUPERS).

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[b] The exam is described fully in the P-117, the Navy Manual of the Medical Department (MANMED), section 15-106, which specifically covers medical requirements for submariners.

Some key factors to consider when deciding upon a waiver for a potentially disqualifying condition are: (1) the extent to which the condition will affect the individual's ability to do the job, (2) the need for ongoing treatments and the ability to provide those treatments underway, (3) the ability of the submarine IDC to provide treatment for a condition were it to flare up while underway, and (4) the probability that the Sailor will experience an acute episode requiring a MEDEVAC while underway. These four considerations are evaluated by an experienced board-certified physician with respect to the U.S. Navy regulations and the available medical evidence. The MEDEVAC consideration is especially important because medical evacuations could pose a risk to the mission and to the safety of the crew and rescue personnel.

4.1.2 Mental Health

Mental health care is a major component of submarine medicine. The physical strains imposed by the submarine environment (close quarters, limited access to fresh food, etc.), the isolation from family/friends while underway, and the demands of the mission can cause psychological stress for submarine crews. When people work long hours in isolation from friends and family, they may have more difficulty adjusting or dealing with life crises. These problems have been seen in other populations, such as researchers living in the Antarctic.[40] These stressors are compounded in a submarine environment by the limited access to mental health providers while underway and the fear that accessing mental health care ashore may have detrimental career effects.[41] A study by Brasher et al., examined specific occupational stressors in Royal Navy submariners and found that, among other factors, the isolated and restricted environment of the submarine contributed to stress. Nevertheless, the authors concluded that Royal Navy submariners were not more stressed than other Royal Navy personnel.[42]

A psychological screening program is used to assess potential submarine candidates when they first enter Basic Enlisted Submarine School (BESS). This screening program is designed to identify candidates who may have problems while serving on submarines. This early identification is intended to benefit the Navy by preventing Sailors from entering a profession to which they are not suited and enhancing the readiness of submarine crews that go underway. The screening is performed on submarine candidates in the form of a survey to identify individuals who are not suited to submarine duty. The annual UPL rate for enlisted Sailors is 3.6%[43] with 28.4% of these UPLs across the Submarine Force attributed to psychological factors. These numbers have been declining over the last several years.[43] Investigators have looked at mental health and personality trends in submariners going back decades, employing screening metrics such as the Minnesota Multiphasic Personality Inventory (MMPI)[44], the Schedule for Nonadaptive and Adaptive Personality (SNAP),[45] outpatient mental health morbidity statistics,[46] and the SUBSCREEN assessment (which was developed in 1986)[47] to identify psychopathology. It should be noted that the SUBSCREEN program is not only intended to identify psychopathology, but also to identify personality traits that could make an individual poorly suited to the submarine environment (i.e., antisocial traits, neuroticism, anxiety, and claustrophobia among others). A problem that remains to be solved is the identification of Sailors who require mental health treatment as a result of newly developed mental illnesses, extraordinary life events, etc.

Several creative solutions are being pursued to better support the mental health needs of the submarine force. For example, mental health providers have been embedded at the waterfront clinic alongside other medical providers so that they can be readily available to submariners with mental health concerns.[48] Other programs have developed emotional support tools that can be used underway to help Sailors deal with mental health crises.[49] These tools use a computer interface to allow Sailors to go through activities such as cognitive behavioral therapy to help them cope with stresses, conflicts, or emotional problems. These tools have also been developed for use in the remote setting of outer space where access to mental health care is similarly challenging.[50-52] These solutions are in development and research is underway to determine their efficacy.

Substance abuse also falls within the realm of mental health. Several investigators have examined the rates of substance abuse in submariners compared to other populations, such as surface Sailors. Burr et al., examined the hospitalization rates of submariners and surface Sailors in five different occupational groups for substance abuse and found that the hospitalization rates were lower for submariners.[53] The authors of the report conclude that the lower substance abuse rates in submariners may be due to (1) more stringent screening of candidates for submarine service (including psychological screening, which may remove individuals most at risk), (2) the fact that submariners tend to have higher levels of education than their surface fleet counterparts, and (3) the hazardous nature of the submarine environment which requires the submarine community to be less tolerant of disciplinary problems. In the 1970s, Weybrew et al. surveyed submariners to ascertain their attitudes about substance abuse and found those who admitted to prior drug use had more permissive attitudes.[54] We are not aware of a more recent survey of submariners concerning this issue, but a 2007 study with Navy personnel revealed that occupational factors are related to positive normative beliefs for heavy and episodic drinking during liberty as well as year-round alcohol consumption.[55]

4.1.3 Radiation Health

The cornerstone of the radiation health program is occupational monitoring for radiation exposure. One portion of the monitoring program is the Radiation Medical Exam (RME), which is performed on all nuclear propulsion workers aboard the submarine. Submariners that only occasionally enter the section of the boat that contains the nuclear reactor are classified as limited radiation workers and are exempt from the RME requirement. The purpose of the RME is to screen for cancerous or precancerous conditions. An RME is performed upon entry into the radiation health program, then every five years up until age 50, every two years after age 50, annually after age 60, and upon exit from the program. The exam includes questions regarding cancer and exposure to ionizing radiation outside of work. Medical tests performed as part of the exam include complete red and white blood cell counts, a urine blood screen, skin exam, thyroid exam, testicular exam, breast exam for women over the age of 40 and a prostate exam for men over the age of 40.[56]

The purpose of the monitoring program is to ensure that Sailors are not exposed to unsafe levels of radiation. As part of the radiation health monitoring that occurs aboard the submarine, each Sailor wears a TLD. The Sailor's dose of radiation is reported for each quarter and also for each year. The IDC aboard the submarine is responsible for maintaining the dosing records as well as distributing and collecting the TLDs. It is important to note that the radiation exposure submariners receive is much lower than the exposure the average American receives from natural background radiation and medical procedures.[57]

4.1.4 The Submarine Atmosphere

An additional source of occupational exposure aboard the submarine is the air that the Sailors breathe. The submarine atmosphere is a closed-loop system that is not replaced with outside air until resurfacing. When the boat is underwater and the air on the ship is not ventilated from the outside, the circulating air is scrubbed of contaminants and oxygen is replenished through electrolysis of water. There are several sources of potential atmospheric contamination aboard the submarine, including oil particulates (produced by machinery and lubricants), organic compounds (released by personal care products), human flatus, respiratory irritants such as acrolein (released from cooking oils and other sources), and compounds such as benzene (which can be found in fuels, lubricants, and other products).[58] Previously, cigarette smoke was a major source of atmospheric contamination, but smoking and vaping are now banned aboard U.S. submarines.[59] The Nuclear Powered Submarine Atmosphere Control Manual provides an overview of some of the compounds of interest and their relevant detection limits.[36]

The atmospheric monitoring equipment aboard the submarine includes the Central Atmospheric Monitoring System, which contains a mass spectrometer capable of quantifying the levels of many different compounds. In addition, NSMRL maintains the Submarine Atmospheric Health Assessment Program (SAHAP). This program places absorption badges aboard submarines, which hang for 5 to 28 days, passively sampling the atmosphere (the duration of exposure of the badge depends on the compound being measured). After exposure, the badges are taken down and sent for analysis when the boat researches port.

There have been numerous studies of the submarine atmosphere, including those evaluating the atmospheric constituents of new classes of submarines (in particular the Virginia-class),[60] and animal studies to identify any adverse effects the submarine atmosphere may pose to female Sailors and their potential offspring.[61] The animal studies found that rats exposed for 28 days to breathing air with slightly elevated carbon monoxide (CO) and carbon dioxide (CO_2) levels showed little if any adverse health effects in them or their offspring. Additional studies on the presence of fine particles in the submarine atmosphere found that the living spaces of the submarines contained lower ultrafine particle levels than those found inside a house.[62]At least one case report examined the potential role of benzene exposure aboard submarines in the development of leukemia in a Royal Navy submariner and concluded that the increased risk of developing leukemia from exposure to the submarine environment was very small.[63] Any significant changes to materials or processes aboard submarines could introduce new atmospheric contaminants, and therefore should be evaluated carefully.

The submarine atmosphere is generally considered safe; one submarine atmosphere ultrafine particle study found that the particle levels were lower than those found on land.[62] However, one of the challenges in analyzing and studying the submarine atmosphere is that exposure limits provided by regulatory agencies are often based on an 8-hour workday, whereas submariners are exposed to the submarine atmosphere around the clock. Understanding exposures in this context is very different from typical monitoring that is performed for occupational hazards.

4.1.5 Health Promotion

Like most U.S. citizens, the Sailors aboard submarines can benefit from health promotion initiatives, such as maintaining a healthy weight and diet, and refraining from the use of tobacco products. Losing weight, following a healthy diet, and quitting smoking are recommended courses of action for people with metabolic syndrome (a cluster of symptoms that can increase one's risk of developing cardiovascular disease). A study from 2009 examined the prevalence of metabolic syndrome among submariners compared to age-matched controls using data from the 2005-2006 National Health and Nutrition Examination Survey.[64] The data on submariners were taken from Periodic Health Assessments (yearly health screening required for all active duty Sailors) of submariners stationed in Groton, CT. The findings from this work showed that submariners had lower markers for metabolic syndrome, including body mass index (BMI), fasting blood glucose, and blood pressure (versus age-matched controls).[64] Despite these results, risk factors for metabolic syndrome, such as limited physical activity and circadian rhythm disruption, have been identified in the submarine population[65]; therefore, there is an opportunity for health promotion in terms of weight loss and physical activity. Furthermore, with respect to diet, submariners have the particular challenge of not having access to fresh food for extended periods of time while underway. As covered above, this is an additional area of concern for the development of obesity and metabolic syndrome.

Submariners can benefit from increased knowledge of the effects of sleep loss and changes in circadian rhythm. Research suggests that sleep deprivation and shifting watch schedules can contribute to increased risk for metabolic syndrome.[65] Additionally, the ability of submariners to exercise while underway is limited due to the space constraints aboard the submarine. A pedometer study performed by Bondi et al. revealed that the activity of submariners was reduced by approximately 50% while underway.[66] A similar study was conducted with South Korean submariners and found an even greater decrease in activity level as measured by pedometers.[67] However, another study the same year as Bondi et al. found no significant weight changes while underway.[68] Moreover, a more recent study showed a decrease in body mass and body fat.[69] Submarines often have only a single treadmill and stationary bike for over 120 crew members. This fact, combined with the limited space and strenuous work hours, can make exercising difficult. Despite these factors, a retrospective study by Gregg et al., found lower Physical Readiness Test[c] (PRT) failure rates among submariners as compared to Sailors on aircraft carriers.[70]

4.1.6 The Submarine Environment and Human Performance

Although not as traditional a medical concern, the effect of the submarine environment on human cognitive performance is one of the most important health and mission readiness concerns aboard submarines. For example, the length of watch shifts can affect attention and performance and may lead to critical mistakes if Sailors become fatigued or suffer attention lapses from too much time spent on a task. One topic that has been studied is the optimal watch schedule (i.e., how much time Sailors should spend on a shift and how much rest they should get in between shifts). This is a complex problem requiring consideration of optimal human performance and the operational concerns of the boat. Studies have compared 18-hour watch schedules to 24-hour watch schedules and found greater degrees of disruption with 18-hour schedules (6 hours on and 12 hours off).[71] Another study used salivary cortisol levels to compare a traditional 18-hour watch schedule to an alternative rotating watch schedule, i.e., a schedule that changes from 6 hours on, 6 hours off, 6 hours on, to 2 hours off, 6 hours on, 6 hours off, to 6 hours on, 24 hours off. The alternative rotating schedule (which would be less operationally compatible) was not found to be superior to the 18-hour schedule by the cortisol metric.[72] Reini et al. reviewed the potential for hypercortisolism in submariners and also provided strategies for mitigating its effects.[73] An additional report examined the design choices in the construction of submarines and how they can lead to effects on human performance. The authors considered, for example, how rack (bed) size may affect the ability of a submariner to sleep (and how size requirements may be changing due to the obesity epidemic in the U.S.), and how the design of a sonar station may affect crew member vigilance.[74]

Several studies, particularly at the time of the introduction of nuclear powered submarines (where Sailors stayed submerged for extended periods), examined the effects of long submergence (90+ days) on human physiology. For example, one study looked at the effect of blood clotting and failed to detect a difference over the course of a patrol.[75] Two areas of interest include CO_2 metabolism and vitamin D metabolism. Schlichting et al. examined the use of vitamin D supplements in submariners and found that those taking supplements maintained their vitamin D levels better than controls taking a placebo supplement (whose levels declined).[76] However, more recent studies question whether vitamin D supplementation makes a difference for health outcomes.[77,78] Davies et al. examined calcium, CO_2 and vitamin D metabolism underway and found that elevated submarine CO_2 levels could contribute to calcium retention,

[c] This is a semi-annual evaluation of basic fitness for duty for all active duty Sailors

but this may be offset by depletion of vitamin D levels, which may reduce calcium retention.[79] Calcium metabolism and vitamin D production have the ability to affect fracture risk.[80] An Israeli study looked at fracture risk in diesel submariners, and detected no increased risk after an underway period.[81] Gertner et al. reviewed vitamin D metabolism and supplementation as well as previous work in this field with submariners, and recommended vitamin D supplementation in submariners.[82] Additional studies by Gasier et al., examined the use of vitamin D supplementation in submariners along with changes in markers of bone density and bone mineralization. The main findings of the studies were that low vitamin D levels did not lead to detectable adverse effects on skeletal health.[83,84] Nevertheless, future research may conclude that vitamin D supplementation is warranted among submariners for other reasons (e.g., due to beneficial effects on mood or sleep).

Studies have looked at the potential physiological effects of elevated CO_2 levels in the submarine atmosphere. One effort found an increase in respiratory dead space during a submarine underway, likely due (in part) to elevated CO_2 levels.[85] It is important to note that this is an older study, which may not be as applicable to modern submarines given the improvements in atmospheric handling equipment. An additional study was devoted to understanding how elevated levels of CO_2 may adversely affect tasks inherent to the submarine mission, but detected no adverse effects on cognition up to the 15000 ppm upper level used in the investigation.[86]

Calcium metabolism is strongly related to kidney stone formation. Kidney stones are a major concern for the Submarine Force because of their prevalence, potential severity, and difficulty to treat underway. In an NSMRL study, Perotta et al. performed a retrospective analysis of kidney stone waivers and disqualification packages. They found that the rate of metabolic abnormalities in submariners (53%) was higher than estimated by medical officers prior to the report and that it was high enough to warrant a thorough work-up to screen for these abnormalities prior to a waiver being considered.[87] The authors also cite literature that suggests lower urine output may contribute to stone formation, which may be an issue for submariners working long shifts with limited fluid intake. In a related study, Dlugos et al. looked at risk factors for renal stone formation over an underway period (by analyses of 24-hour urine samples and parathyroid hormone levels, among others) and found that renal stone formation was exacerbated by the submarine environment.[88]

4.1.7 Long Term Health Effects of Submarine Service

The submarine environment and submarine service exposes individuals to conditions that are not encountered by the general population. Understanding potential long term health risks from these conditions is extremely important to ensure we can place exposed individuals into appropriate monitoring programs and implement procedural changes and engineering controls to mitigate or prevent future harmful exposures. A key focus of submarine medicine is understanding these long-term health effects from a population-based/epidemiological perspective and reducing any ill effects that are discovered. The effects of potential toxins in the submarine atmosphere, lack of vitamin D and disorders of calcium metabolism, and cardiometabolic health have been mentioned previously. Additional long-term health impacts of interest include cancer, mortality, and reproductive health. An issue related to reproduction is the question of whether submariners have more female offspring. A survey of submariners implies this may be so, but a comprehensive review of medical records does not.[89,90]

A question of interest to the submarine medical community is whether U.S. Navy personnel, including submariners, have an increased risk of contracting cancer. Two studies of cancer deaths among submariners (who served between 1969 and 1995) failed to find evidence of increased cancer deaths, compared to the civilian population.[57,91] Several cancer-related studies of non-U.S. navies have compared navy personnel and the general population, and were able to specifically compare submariners to other naval sailors. Strand et al. found a slightly elevated cancer incidence among Norwegian navy personnel as compared to the general population, and a higher incidence of bladder cancer among Norwegian submariners as compared to Norwegian sailors on other platforms.[92] The authors attributed the slightly higher incidence of cancer to better screening of military personnel. The authors also speculate that the higher rate of bladder cancer among submariners, as compared to sailors, was due to diesel exhaust exposure. However, the authors point out that the link between diesel exhaust exposure and bladder cancer is not strongly based in evidence.[92] As part of their study, Strand et al. also examined non-cancer mortality rates and found them to be lower than, or on par with, those of the general population.[92] Inskip et al. published a mortality study of Royal Navy submariners and found that the overall mortality was lower when compared to male non-submariners from England and Wales, and that cancer mortality was also lower. It was noted that submariners had a higher incidence of death from “digestive diseases” (p. 211) mainly attributed to liver cirrhosis and accidents, but these findings cannot be linked conclusively and directly to the submarine environment and submarine service. For those in the study group who died from liver cirrhosis, alcohol consumption was specifically mentioned on the death certificate in over half of the cases.[93]

Additional studies have investigated various long-term health indices of submariners. One report on health risks among submariners from 1974-1979 found a lower overall hospitalization rate among submariners.[94] This finding, however, is confounded by the more stringent health screening process that submariners must undergo to qualify for submarine duty. Kang and Song performed a cross-sectional study and examined the prevalence of multi-morbidity (defined as having two or more chronic health conditions) among South Korean submariners and found that the multi-morbidity rate was significantly higher than the general population (by almost 3 times).[95] A survey-based study examined the effects of submarine service on reproductive health and the ratio of male to female offspring, but found no statistically significant difference between submariners and the general population.[96]

4.1.8 Medical Considerations during Submarine Escape and Rescue

Although rare, disabled submarine incidents happen occasionally and trigger an international response, usually assisted by the International Submarine Escape and Rescue Liaison Office. This response often entails the mobilization of U.S. rescue and medical assets and presents unique medical challenges compounded by the submarine environment, even when the event is not a U.S. submarine mishap (e.g., the ARA San Juan sinking in 2017).

One paper is publicly available that describes field treatment after a mass-casualty event aboard a U.S. submarine, after the USS San Francisco struck an undersea mount while operating in a remote area of the Pacific Ocean in 2005.[97] In the case of the U.S. Navy, recent mishaps have not led to extensive casualties, but prior to the 1970s, U.S. submarine crews have been lost (e.g., the USS Scorpion, lost in 1968; the USS Thresher in 1963). A recent review describes recent submarine mishaps and the medical considerations for prolonged field care of injured Sailors afterwards.[98] An overview of Royal Navy submarine rescue operations is available in the literature as well.[99] The reader is directed to these papers for an overview of submarine incidents, rescue capabilities, and the medical considerations during rescue operations. Some key considerations are highlighted below.

While awaiting rescue is preferred, the decision to stay and be rescued or to attempt escape depends on various factors. A key element is deciding whether escape is necessary or even possible. For example, if the submarine lies too deep in the ocean, escape is too dangerous. If escape is possible, then the decision about when to escape depends on the condition of the crew, the available equipment, who may be on the surface, and the conditions aboard the vessel. Radiation levels, temperature, oxygen levels, internal pressure within the hull, and the levels of seven Submarine Escape Action Limit (SEAL) gases[100,101] all play into this decision.

In some cases, elevated gas levels (such as CO_2) could occur and must be mitigated if possible. Reini et al. looked at the use of propranolol to reduce CO_2 production with the hope of using the medication to improve survivability in a disabled submarine. The intent of the study was to see if the use of propranolol (a beta blocker used to treat conditions such as hypertension) would reduce atmospheric CO_2 levels, thereby increasing the stay time on a disabled submarine (DISSUB) before an escape must be considered or rescue assets must arrive. They concluded that taking 40 mg of propranolol twice daily reduces resting CO_2 production and that doing so in a DISSUB scenario could increase allowable stay times and delay time to escape.[102] Still other studies have estimated the amount of CO_2 produced by survivors within a DISSUB in order to estimate the amount of CO_2 absorptive materials needed to be brought underway.[103]

Two other issues related to DISSUB and submarine escape and rescue are decompression illness and pulmonary oxygen toxicity, which are central to diving medicine. The crossover to submarine medicine occurs because Sailors could be trapped inside a hull that has an elevated ambient atmospheric pressure and be required to return to surface pressure after escape or rescue. Breathing air at elevated atmospheric pressures results in nitrogen dissolving into tissues. The dissolved nitrogen is released from the tissues during ascension, due to the decrease in ambient pressure and the nitrogen pressure gradient that is created. The released nitrogen can generate bubbles that block small blood vessels and/or trigger an inflammatory response, leading to decompression illness.

Like decompression illness, pulmonary oxygen toxicity is a consideration primarily of diving medicine,[104] but it is also relevant to DISSUB for two reasons. First, the pressure inside the hull of a disabled submarine is likely to rise for a variety of reasons (i.e., flooding, release of air from pressurized air banks, use of emergency breathing apparatus, and rising temperatures). This elevated pressure can lead to elevated oxygen partial pressures, which can cause pulmonary oxygen toxicity.[104] Second, treatment of decompression sickness requires breathing high oxygen partial pressures, which can lead to or exacerbate the effects of pulmonary oxygen toxicity.[104] According to the U.S. Navy Diving Manual pulmonary oxygen toxicity can occur at oxygen partial pressures above 0.5 ATA with higher partial pressures leading to quicker time to onset.[104]

4.2 Some Submarine Health Concerns or Gaps Requiring Further Research

There are several medical capability gaps that would benefit from future investigation. They include: improved mental health screening of submarine candidates and periodic psychological reassessment of qualified submariners, remote mental health support resources to aid submariners (suffering from stress, conflict resolution problems, coping problems, etc.),[105] prolonged field care of casualties aboard the submarine,[106] and improved monitoring of the submarine atmosphere.[d] A recurring theme throughout the following discussion of capability gaps is the need for a more centralized repository of submarine health data, including information on (the prevalence and reasons for) submarine MEDEVACs and medical disqualifications.

A summary of the relevant medical needs for all the military services can be found in the Military Operational Medicine Capabilities-Based Assessment Study. This document also contains specific shortfall statements outlining the new capabilities that are needed.[107] Relevant aspects of the submarine environment that are described include undersea vehicle transport issues (sea sickness, lack of sunlight, enclosed space). Topics mentioned as needing attention include the situational awareness of submariners and divers, thermal guidance for submariners and divers, ability to safely rescue submariners, ability to maximize DISSUB survival time, and

[d] Optimizing submarine human factors lies within the fields of psychology and engineering, but is important to the health and safety of submariners also. It is not detailed in this medically-focused review.

ability to determine atmospheric contaminants. There are many other relevant capability/competency documents which point to areas of need in medicine and psychology. For example, the Undersea Warfare Science and Technology Objectives include the optimization of submariner readiness, retention, and health, and resilience, as well as human-machine interfaces.[108]

4.2.1 Improved Mental Health Screening

As previously mentioned, MEDEVACs due to mental health problems remain a concern while underway. Furthermore, many medical disqualifications are due to mental health conditions such as depression and adjustment disorder. Mental health screening is performed to identify submarine candidates who have mental health issues, or who simply may not fare well in the submarine environment, but these screening procedures could benefit from being updated. Furthermore, there is currently no regularly recurring mental health screening other than some basic questions asked during a Sailor's periodic health assessment. There is a need to better screen qualified submariners so that concerns are identified and dealt with before they threaten the health of the Sailor or the mission. Improved solutions and additional periodic screenings are being developed to better address these issues.

4.2.2 Mental Health Support

If they occur, mental health conditions can be difficult to deal with when a submarine is underway, given that a single IDC with limited mental health training is available to assist more than 100 crew members. Even one patient requiring intensive treatment or supervision can overwhelm a single corpsman who has other essential tasks to complete. Tools are needed to extend the reach of the IDC in providing mental health care. One option would be remote mental health applications, which have been mentioned previously (p. 14)[49] and are in development now.[105] These tools provide cognitive behavioral therapy via a computer program. These programs could be downloaded to a secure electronic device ahead of deployment, allowing users to privately access them (e.g., after consultation with the IDC).

4.2.3 Submarine Escape and Rescue

Further study is needed to understand the mechanisms of pulmonary oxygen toxicity and the unique decompression concerns that accompany submarine rescue operations. Treatments or preventative measures for pulmonary oxygen toxicity are needed if the current decompression protocols are used to treat decompression sickness as a result of submarine rescue. Specialized equipment and decompression chambers have been developed that can be transported by air and sea, including the U.S. Navy's Submarine Rescue Diving and Recompression System (SRDRS).[109] There are decompression protocols for different situations, but some of the specialized (e.g., accelerated) decompression protocols for submarine rescue have yet to be fully tested on humans. The literature contains some work that has been performed in this area, including:

- A study that examined the decompression obligation of the rescue personnel,[110]

- A Royal Navy study that simulated escapes and reported injury rates,[111]
- A Royal Navy study that involved decompression illness modeling based on actual and simulated escapes,[112] and
- A study of French military personnel that used human subjects and examined decompression protocols that might be used during a submarine rescue, though no cases of decompression illness were reported during this study.[113]

More work is needed to augment the findings of these studies to improve the safety and extend the reach of submarine escape and rescue capabilities.

4.2.4 Long Term Field Care

As with many other areas of military medicine, it would be ideal to provide high quality care to seriously ill submariners for extended periods of time while underway, thus reducing the need for MEDEVAC and all the associated risks. Strategies to prolong patient life until surgical care is available have been explored primarily in the setting of combat trauma. Future investigations for the submarine force could begin with simpler strategies to care for patients who will eventually require surgical intervention. For example, European studies have indicated that antibiotics are effective against appendicitis with only a fraction of patients requiring eventual operation (though this needs further evaluation in prospective randomized trials).[114,115] A few reports in the submarine population have examined the conservative management of surgical diseases with antibiotics, though these reports need to be updated to reflect current medical practice.[116,117] One major issue in the care of injured patients in the remote setting is limited access to resources, particularly blood products to treat severely injured patients. Devlin et al. proposed an emergency blood donation program aboard submarines, which could be used to treat injured Sailors with severe blood loss.[118] However, this may be impractical presently, due to the absence of a walking blood bank with the capability to infuse.

4.2.5 Fatigue Leading to Performance Degradation

Fatigue is a major challenge across many different professions and is more pronounced in the military, where the pressures of the operational tempo and the need to stay mission ready can lead to long hours with little sleep. Fatigue due to watch schedules were discussed briefly in Section 4.1.6. An important need that has not been filled is the identification of Sailors who have become so fatigued that they cannot adequately perform their assigned tasks. Two recent collisions involving the surface fleet are thought to be partly due to fatigue of those operating the ship, which has brought this issue into the public view.[119,120] Non-invasively identifying fatigued Sailors and devising countermeasures are formidable challenges for the submarine medical research community.[121,122]

4.2.6 Long Term Health Effects of Submarine Service/Improved Monitoring

More population-based research is needed on Sailors who have served aboard submarines to identify disease patterns many years down the road.[123,124] This information, coupled with monitoring data, could be used to tie exposures to disease development. This information is essential to properly monitor exposed individuals, and implement better engineering controls to prevent future exposures.

5 Conclusions

The submarine is the stealthiest and most versatile vessel in the U.S. Navy, and it is critically important to national defense in the 21^{st} century. The effectiveness of a submarine is naturally dependent upon the readiness of the crew that operates it. Ensuring submarine crew readiness is an important mission of submarine medicine, yet no textbooks and few reviews are dedicated solely to this topic. In this report, we have provided an overview of the ways submarine medicine contrasts with other branches of specialized medicine which seek to ensure health, safety, and performance under extreme conditions. We have described the unique challenges and constraints of practicing submarine medicine and the key medical problems of interest in this domain. We hope that this review will increase awareness among medical providers, mental health care providers, and researchers, thereby fostering new collaborations, solutions, and innovations of benefit to Navy submariners.

List of Abbreviations

ACLS - Advanced Cardiac Life Support

AMAL - Authorized Medical Allowance List

BESS – Basic Enlisted Submarine School

BMI – Body Mass Index

BUMED – Bureau of Medicine and Surgery

BUPERS – Bureau of Personnel

CAMS – Central Atmospheric Monitoring System

CNS – Central Nervous System

CO_2 – Carbon Dioxide

COMSUBLANT– Submarine Forces Command Atlantic

COMSUBPAC – Submarine Forces Command Pacific

DISSUB – Disabled Submarine

FMO – Force Medical Officer

GMO – General Medical Office

IDC – Independent Duty Corpsman

IV– Intravenous

MANMED – Manual of the Medical Department

MMPI – Minnesota Multiphasic Personality Inventory

NSMRL – Naval Submarine Medical Research Laboratory

NUMI – Naval Submarine Medical Institute

PRT – Physical Readiness Test

RME – Radiation Medical Exam

SAHAP – Submarine Atmospheric Health Assessment Program

SEAL – Submarine Escape Action Limits

SERP – Submarine Epidemiology Research Program

SSBN – Submarine Ballistic Missile Nuclear Powered

SSGN – Submarine Guided Missile Nuclear Powered

SSN – Submarine Nuclear Powered

TLD – Thermoluminescent Dosimeter

TYCOM – Type Commander

UMO – Undersea Medical Officer

UPL – Unplanned Loss

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