Future directions of infection control and risk management on military vessels: a narrative review

Rebecca K. Brewster[1], Kathy Chan[2], Hannah Allen[3], Alexander Sundermann[4], Scott Keane[5], Corey Boles[6]

[1]Cardno ChemRisk, Chicago, IL, USA; [2]Cardno ChemRisk, Arlington, VA, USA; [3]Cardno ChemRisk, Pittsburgh, PA, USA; [4]Graduate School of Public Health, University of Pittsburgh, Pittsburgh, PA, USA; [5]Cardno, Queensland, Australia; [6]Cardno ChemRisk, Blue Ash, OH, USA

Contributions: (I) Conception and design: RK Brewster, C Boles; (II) Administrative support: RK Brewster, H Allen; (III) Provision of study materials or patients: RK Brewster; (IV) Collection and assembly of data: RK Brewster, K Chan, H Allen, A Sundermann, C Boles; (V) Data analysis and interpretation: All authors; (VI) Manuscript writing: All authors; (VII) Final approval of manuscript: All authors.

Correspondence to: Rebecca K. Brewster. Cardno ChemRisk, 205 W. Wacker Drive, Suite 1500, Chicago, IL, USA. Email: rebecca.brewster@cardno.com.

Background and Objective: Infectious disease outbreaks on military vessels have been a consistent challenge and can result in severe implications for readiness and national security. Crew member duties and the shipboard environment create conditions that may exacerbate disease spread, such as close and frequent contact, enclosed areas, and limited space for isolation. Prior to the coronavirus disease 2019 (COVID-19) pandemic, militaries had established infection control and risk management plans. COVID-19 outbreaks onboard military vessels, however, revealed potential discrepancies between these protocols and responses. The objective of this review is to assess infection control and risk management protocols during COVID-19 outbreaks on military vessels, identify potential gaps in responses, and propose future directions for controlling infection and mitigating risk onboard vessels that align with the principles of infectious disease epidemiology, infection control and prevention (ICP), and industrial hygiene (IH).

Methods: A literature search was performed using the PubMed online database and Google Scholar search engine to identify publications that examined COVID-19 and other disease outbreaks on military vessels, as well as infection control strategies employed by these vessels. A search was also conducted for documents produced by governments and other authoritative agencies that addressed infection control and risk management on military vessels. Only publicly available literature, reports, policies, and other documents published in English were considered for inclusion.

Key Content and Findings: Based on the literature review, existing infection control and risk management protocols were not always fully implemented during COVID-19 outbreaks on military vessels, thus highlighting possible gaps in response. As such, several measures may be considered to reduce the future risk of disease transmission on military vessels, including enhancing disease surveillance tactics, optimizing the shipboard environment, implementing vaccination programs, and developing risk assessment-based and comprehensive infection control and risk management plans.

Conclusions: Existing infection control and risk management policies were reviewed in the context of COVID-19 outbreaks on military vessels. Several strategies that rely on infectious disease epidemiology, ICP, and IH principles were also presented, which may help mitigate the risk of future disease outbreaks onboard vessels, thereby ensuring the safety of crew members as well as protecting national security.

Keywords: Naval; ship; infectious disease; coronavirus disease 2019 (COVID-19); risk mitigation

Received: 09 January 2022; Accepted: 23 April 2022; Published: 25 December 2022.

doi: 10.21037/jphe-22-2

View this article at: https://dx.doi.org/10.21037/jphe-22-2

Introduction

Militaries have historically faced challenges controlling infectious disease transmission among service members (1). Infections caused by exposure to respiratory pathogens (e.g., SARS-CoV-2, influenza) have been particularly prevalent in military operations, including among those serving on naval vessels (2,3). The spread of disease on military vessels and other enclosed environments can be understood in the context of two infectious disease epidemiology paradigms, the chain of infection (CoI) and the epidemiologic triangle. In the CoI, pathogen transmission occurs when an agent (e.g., pathogen) leaves a host reservoir through a portal of exit (e.g., respiratory tract), is transferred through a mode of transmission (e.g., droplets, airborne), and infects a susceptible host through a portal of entry (e.g., respiratory tract) (4). However, the ability for a pathogen to successfully leave a host reservoir and infect a new host depends not only on agent- and host-specific factors but on environmental factors as well. The relationship between agent, host, and environment is highlighted in the epidemiologic triangle model, in which disease may result from the interaction between an agent (e.g., pathogen) and a susceptible host (e.g., an individual), in an environment where the physical, biological, and socioeconomic conditions support agent transmission and host exposure (5). As such, the vessel environment plays a critical role in the potential for disease transmission.

Due to the unique conditions present on vessels, disease outbreaks are not uncommon. In the cruise ship industry, for example, gastrointestinal illness outbreaks have been a consistent public health concern, and military vessels have faced similar challenges along with respiratory illnesses (6,7). Historically, the most relevant and widely documented example of infectious disease outbreak aboard military vessels occurred during the 2009 H1N1 influenza pandemic. Outbreaks among military personnel were documented on the United States Ship (USS) Iwo Jima, USS Roosevelt, USS Bonhomme Richard, USS George Washington, and USS Ronald Reagan, and other unspecified vessels (8-12). Attack rates during these H1N1 outbreaks varied widely among vessels, from less than 1% to approximately 22%, which may be due to differences in vessel type, control interventions, case definitions, and available data (8-12). The isolated and enclosed nature of these vessels caused unique infection control and prevention (ICP) challenges and increased transmission rates. Specifically, the lack of fresh air or ventilation inside vessels, lack of space for isolating sick individuals, and limited medical supplies and personal protective equipment (PPE) resulted in reports of viral transmission (9-11). Vessels operating during the H1N1 pandemic also reported daily activity disruption due to staffing constraints and low morale as consequences of such outbreaks (10). Similar to the observed H1N1 outbreaks, coronavirus disease 2019 (COVID-19), a highly infectious respiratory disease caused by the novel coronavirus SARS-CoV-2, began spreading aboard military vessels in the pandemic's early months. Much of the information related to COVID-19 outbreaks on military vessels has been restricted by national authorities to maintain operations security, but several outbreaks, including those on the aircraft carriers USS Theodore Roosevelt and the Charles de Gaulle, have been characterized and analyzed to improve vessel infection control measures (13-15).

Vessel conditions, in general, create an environment that may increase the risk of disease spread due to poor ventilation and confined spaces where service members work, eat, socialize, and sleep, which provide little to no room for physical distancing (3,15,16). Additionally, the nature of shipboard work often requires multiple individuals to accomplish tasks and assigned duties. These conditions create opportunities for close and frequent contact, thereby increasing the risk of disease transmission. Although isolating and quarantining infected service members is a vital tool for reducing disease transmission, vessels have finite space with limited room for isolation and quarantine areas. Further, deployed vessels often operate far offshore, posing challenges for promptly removing infected individuals, and directly impacting vessel operations (17). These factors combine to present a complex environment that can lead to increased infectious disease transmission risk during vital operations, which in turn could potentially compromise service member health, and, by extension, national security.

Outbreaks on military vessels not only pose a direct risk for those onboard, but also disrupt military operations, which can create a national security concern. Military vessels should therefore have comprehensive, multi-layered, and flexible infection control plans in place that rely on epidemiology, ICP, and industrial hygiene (IH) principles, and can be swiftly implemented in the face of an outbreak (16,18,19). Plans and protocols should account for various agent-, host-, and environment-dependent factors which can influence disease transmission, such as the specific pathogen's mode of transmission (e.g., droplet, airborne), crew members' susceptibility of infection (e.g., work practices), and the vessel's size, type, and mission (5). Further, IH paradigms, such as the United States (U.S.) National Institute for Occupational Safety and Health's (NIOSH) Hierarchy of Controls (HoC), can be used to select and apply controls that target key points in the CoI (e.g., the host reservoir, transmission pathway, and susceptible host), which may help "break the chain", thereby slowing the spread of disease (18). Across many sectors, implementing effective and comprehensive infection control and risk mitigation strategies has been a consistent challenge to controlling SARS-CoV-2 transmission. Prior to and during the COVID-19 pandemic, the U.S. Department of Defense (DOD) maintained instruction for the management of public health emergencies, which included instruction regarding the redirection of facilities and materials for emergency use and implementation of restriction of movement (ROM) (20). In addition, the U.S. Navy also maintained specific infection control plans, including the Pandemic Influenza and Infectious Disease Policy and Healthcare-Associated Infection Prevention and Control Program (21,22). Lastly, militaries oftentimes relied on expertise from government agencies in their respective countries to support infection control response (23,24).

The purpose of this study is to review infection control policies and procedures pertaining to military vessels, assess the steps taken by various militaries to control SARS-CoV-2 transmission onboard vessels, and use infectious disease epidemiology, ICP, and IH principles to offer insights into future directions for infection control and risk management for COVID-19 and other infectious diseases. This review is focused specifically on the spread and control of infectious disease onboard military vessels, and does not address the impacts of exposure, transmission, and control of disease pre-deployment, post-deployment, or during shore leave. We present the following article in accordance with the Narrative Review reporting checklist (available at https://jphe.amegroups.com/article/view/10.21037/jphe-22-2/rc).

Methods

A literature search was conducted on October 5, 2021 in the PubMed online database to identify available studies that analyzed outbreaks of COVID-19 and other historical infectious diseases aboard military vessels, as well as ICP measures utilized by vessels to prevent such outbreaks. Keywords used to identify studies relevant to military vessels included "military vessel(s)", "naval vessel(s)", "naval ship", "warship(s)", "military", and "Navy ship". Search terms related to infection prevention included "infection control", "infection prevention", "sanitation", "risk management", "outbreak preparedness", "outbreak response", "pandemic preparedness", "pandemic response", and "outbreak". Additional searches included keywords specific to COVID-19 and were derived from the Centers for Disease Control and Prevention (CDC) COVID-19 PubMed search alert, including "coronavirus", "corona virus", "covid19", "covid 19", "COVID-19", "Coronavirus", and "pandemic" (25). The PubMed literature searches were crosschecked in the Google Scholar search engine to ensure that all relevant papers were captured. An additional search was conducted to identify publicly available reports, policies, and other documents released by governments and other authoritative organizations that addressed infection control on military vessels. Searches were limited to papers published in the English language. All articles published prior to October 5, 2021 and article types were considered for inclusion. This review only considered publicly available data, studies, reports, and protocols. Publications that met the inclusion criteria were initially reviewed, and publications that addressed previous disease outbreaks of H1N1 on vessels, COVID-19 outbreaks on military vessels, military ICP policies (including for COVID-19), and lessons learned from disease outbreaks were selected for inclusion. All authors were involved in the review and selection of literature. A summary of the literature search strategy is provided in *Table 1*.

Discussion

A limited review of historical respiratory outbreaks and infection control policies on military vessels, as well as recommendations for the future of infection control on military vessels, are presented herein. The infection control and risk management strategies described in this review rely on epidemiology, ICP, and IH principles, to help reduce the risk of disease transmission.

Infection control and risk management techniques employed on military vessels during disease outbreaks

Infection control and respiratory disease outbreaks

Prior to the COVID-19 pandemic, militaries had established health and safety, infection control, and risk mitigation plans for use in the event of disease outbreaks. The U.S. Navy's Navy Safety and Occupational Health Manual is an example of a comprehensive health and safety

Table 1 Summary of the literature search strategy

Items	Specification
Date of search	October 5, 2021
Databases and other sources searched	PubMed, Google Scholar
Search terms used	("military vessel" OR "naval vessel" OR "naval ship" OR "warship" OR "military" OR "Navy ship") AND ("infection control" OR "infection prevention" OR "sanitation" OR "risk management" OR "outbreak preparedness" OR "outbreak response" OR "pandemic preparedness" OR "pandemic response" OR "outbreak") AND ("coronavirus" OR "corona virus" OR "covid19" OR "covid 19" OR "COVID-19" OR "Coronavirus" OR "pandemic")
Timeframe	All dates prior to October 5, 2021
Inclusion and exclusion criteria	Documents published in the English language during or before October 5, 2021 were included in this review. No additional restrictions were placed on study type or publication date
Selection process	All authors were involved in the review and selection of literature in alignment with the specified inclusion/exclusion criteria
Any additional considerations	Publicly available government documents related to infection control and prevention policies on military vessels were also reviewed from the Centers for Disease Control and Prevention, U.S. Department of the Navy, U.S. Department of Defense, U.S. Marine Corps, and Australian Department of Defence

plan, which addresses several topics, including chemical, physical, and biological hazards for U.S. Navy personnel on land and at sea (26). Additionally, the U.S. DOD set forth a directive regarding Force Health Protection, which defines responsibilities associated with establishing, sustaining, restoring, and improving overall force health (27). This directive includes instruction regarding immunizations, as well as routine inspection and mitigation of industrial, occupational, operational, and environmental hazards and exposures. Further, since 2002, the Naval Health Research Center (NHRC) has conducted febrile respiratory illness (FRI) surveillance on U.S. Navy vessels, which detects respiratory pathogens and specific etiologies and monitors respiratory illness incidence (2).

The U.S. DOD maintains specific instructions for the management of public health emergencies, updated in 2019, which provides an algorithm for decisions regarding public health emergencies, outlines communication chains and notification routing, and defines military Commander emergency health powers (20). Additionally, U.S. Naval authorities have specifically set forth policies surrounding pandemics and infectious disease, including a Healthcare-Associated Infection Prevention and Control Program issued in 2011, as well as a Pandemic Influenza and Infectious Disease Policy issued in 2018 (21,22). These policies define factors for evaluating the operational significance of a disease outbreak, the scope of responsibilities for various agents, and details regarding resources and logistics, infection and medical surveillance, laboratory support, immunization, and records management (21,22). Therefore, established frameworks have been in place over the last 10 years at both the level of the U.S. DOD and the U.S. Navy.

One recent occasion during which infection control measures on military vessels were implemented was the 2009 H1N1 pandemic. While removing sick patients to an offboard medical facility was an effective technique used to prevent disease spread and maintain available space in infirmaries and sick wards, this was not always possible (8,10). Outbreaks aboard the USS Ronald Reagan and the USS George Washington, for example, occurred while the vessels were out at sea. Medical personnel aboard these vessels originally aimed to isolate sick individuals, but, because of space constraints, patients were returned to their normal quarters on "sick in quarters" status or kept in the infirmary for a reduced duration (11). Additionally, while face masks were issued to recovering patients to wear in public quarters on the USS George Washington, USS Iwo Jima, and USS Roosevelt, face mask supplies were too limited aboard the USS Ronald Reagan to be implemented as a control measure (8,11). Additional infection control measures implemented during H1N1 outbreaks aboard military vessels included increasing disinfection of surfaces, distributing hand sanitizers, enhancing symptom surveillance systems, and educating personnel on proper hygiene and handwashing (8,10-12). Outbreak investigations during the H1N1 pandemic exemplified the unique challenges associated with the lack of available resources aboard vessels at sea.

COVID-19 outbreaks and additional infection control measures

Since the onset of the COVID-19 pandemic, military vessels have faced similar challenges with preventing and controlling outbreaks, as with previous diseases (e.g., H1N1). Two notable and well-described examples of COVID-19 outbreaks on military vessels include the USS Theodore Roosevelt, an American nuclear aircraft carrier, and the Charles de Gaulle, a French nuclear aircraft carrier (3,13-15,17,28,29). The COVID-19 outbreaks occurred between March and May 2020, and attack rates were reported as high as 26% and 64% on the USS Theodore Roosevelt and Charles de Gaulle, respectively (13,14,17,28,29). Both vessels represent examples and case studies of early-stage outbreak responses in the pandemic, and were challenged by the lack of scientific information about the transmission of SARS-CoV-2 and the necessary tools for detecting and controlling COVID-19 (e.g., testing, vaccines).

Kasper and colleagues reported that the first positive tests for COVID-19 on the USS Theodore Roosevelt were received on March 23, 2020, forcing the vessel to dock in Guam on March 27, 2020 (14). The outbreak lasted for an additional six weeks. As such, several response measures were executed to mitigate the spread of SARS-CoV-2 on the vessel, including testing procedures (once available), contact tracing, and quarantine and isolation practices. Subsequent to testing, COVID-19 confirmed crew members were isolated, and crew members with one or more negative COVID-19 test results were quarantined separately on base. Additionally, crew members were surveilled via a system that incorporated in-person health screenings and self-reporting through a symptom checker, and resulting data were analyzed each morning and evening. Crew members became eligible for exit testing after they isolated or quarantined for 14 days, and those in isolation were also required to be symptom-free for three days (14).

In contrast, as discussed by Chassery and colleagues, precautionary measures were implemented on several occasions in advance of the COVID-19 outbreak aboard the Charles de Gaulle (13). On February 29, 2020, the Commander of the Charles de Gaulle implemented health measures recommended by the French Armed Forces Health Service, including health checks and medical monitoring. The Commander went forward with a stopover in Brest on March 13, 2020, but exercised the following precautions: on board visits were prohibited; seamen who went ashore were forbidden to enter areas of high SARS-CoV-2 transmission; and all members joining the vessel had to complete an exposure risk assessment questionnaire. The following day, the Commander established physical distancing measures, less frequent briefings, restrictions on the number of individuals in group settings, and new sports rules. On March 30, 2020, however, the Commander relaxed health measures, and allowed a concert to be held on the vessel. On April 5, 2020, a crew member who had sailed on the Charles de Gaulle tested positive for COVID-19, and the vessel docked in Toulon, France on April 13, 2020. After receipt of the first positive test, strict health and safety measures were resumed, all individuals with possible cases of COVID-19 were isolated, and a team of epidemiologists arrived on board to conduct testing. At the Toulon port, all COVID-19 confirmed crew members were isolated on shore (13).

The COVID-19 outbreaks on the USS Theodore Roosevelt and Charles de Gaulle illustrate gaps in military infection control plans and responses to disease outbreaks on vessels. An investigation into the USS Theodore Roosevelt revealed that physical distancing was not effectively implemented, quarantine periods were insufficient onboard the vessel, and that such actions were inconsistent with U.S. Navy guidance at the time (30,31). Regarding outbreak handling on the Charles de Gaulle, Chassery and colleagues reported that disseminating information and recommendations was complicated by evolving clinical criteria for diagnosis, the absence of recommendations on how to use available diagnostic tools, and the subsequent late detection of the epidemiological signal, thus leading to "gaps in benchmarks for decision-making" (13). Further, the Commander chose to manage the situation internally prior to alerting authorities, thereby isolating streams of communication. Existing infection control, risk management, and epidemic crisis management plans were therefore recommended to be updated to reflect the lessons learned from COVID-19 outbreaks on vessels early in the pandemic, noting that the best practices for planning, logistics, and medical response may vary depending on the type of ship (13,30).

General infection control guidance documents were updated, and specific COVID-19 plans were created to address the gaps demonstrated during the COVID-19 pandemic. Specifically, the U.S. Navy implemented controls such as increased cleaning and sanitation protocols, physical distancing, quarantining, and ROM (31). In April 2020, the U.S. Navy implemented several frameworks for preventing, mitigating, and recovering from COVID-19, as well as pre-deployment guidance targeted to deployable units and enabling commands (32-35). These frameworks, which were updated periodically, offered guidance specific to the vessel environment, such as routine cleaning and disinfecting, inventorying and utilizing PPE, minimizing port visits, prohibiting large gatherings and training drills, practicing physical distancing, complying with quarantine measures, evacuating high-risk personnel, and staying informed of applicable guidelines (32,33).

Following the USS Theodore Roosevelt outbreak, the U.S. Navy incorporated several lessons learned to enhance vessel safety, including placing crew members on ROM for 14 days, requiring diagnostic testing prior to deployment, and reducing shore leaves at foreign ports (14). In June 2020, the U.S. Navy published the COVID-19 Leader's Handbook, which presented information on topics including contact tracing, testing, prevention and containment, and fleet lessons learned, to help officers implement data-driven risk prevention and mitigation strategies (30). In July 2021, the Chief of Naval Operations updated the Pandemic Influenza and Infectious Disease Policy, now referred to as the Pandemic and Infectious Disease Policy, to incorporate notable lessons learned from the COVID-19 pandemic (36). Additional responsibilities in the policy included a call to publish emergent or supplemental guidance related to ROM, return to work, and vaccine distribution and administration; the ability to activate a specialized crisis action team; and improved coordination methods among various agents. The existence or availability of rapid and accurate diagnostic testing was added to the factors to consider when evaluating the operational significance of a disease outbreak. Furthermore, throughout the pandemic, the U.S. Navy and U.S. Marine Corps released policies addressing various topics relating to COVID-19, including, but not limited to, face masks, testing, reporting requirements, deployment procedures, movement and travel, and vaccinations (30,37,38).

Future directions for infection control and risk management on military vessels

Incorporating lessons learned from COVID-19 outbreaks into infection control and risk management plans, which some militaries have done, informs leaders to more effectively address future outbreaks of respiratory pathogens. Strategies that should be considered to prepare for and mitigate future disease outbreaks include increased disease monitoring and surveillance, optimized vessel design, vaccination programs, and collaborative infection control planning. Agent, host, and environmental factors, including vessel type, size, and mission, should be considered when developing protocols and implementing control measures. The strategies presented herein are not exhaustive, rather, several practices that are grounded in the principles of infectious disease epidemiology, ICP, and IH and could be implemented on military vessels are highlighted.

Disease monitoring and surveillance

Disease surveillance can serve multiple purposes, including detecting new pathogens that may pose a potential outbreak threat, monitoring the spread of identified diseases, and evaluating the extent and severity of an ongoing disease outbreak (16). Early detection of disease outbreaks onboard vessels is therefore critical for mitigating transmission, as it provides invaluable insight into the transmission dynamic and allows for the opportunity to implement intervention methods to help reduce disease spread. The NHRC's FRI shipboard program, for example, helped service members detect and respond to a 2014 H3N2-associated influenza outbreak on a U.S. Navy minesweeper (2). In fact, Vicente and colleagues recommended several early interventions to mitigate disease outbreaks on military vessels, including implementing early recognition systems and using shore-based preventive medicine teams to assist with contact tracing and quarantine measures (15). The ability for crew members to effectively survey and assess disease spikes, however, is limited by the number of trained medical crew members onboard (31). Therefore, vessels should staff sufficient medical crew members. Militaries may also consider training additional crew members to carry out outbreak investigations, including disease monitoring and contact tracing. For example, training for outbreak investigation and contract tracing are included in the current U.S. Navy guidance for COVID-19, which mandates that no fewer than two service members be trained in this area for each command (39).

New tools and resources are also available for disease surveillance. The CDC, for example, has made significant advances in using wastewater surveillance to detect and measure COVID-19 burden within a community (40). This approach often uses municipal wastewater testing to model the number of community infections, and can be adapted to individual buildings or a group of buildings, such as college campuses (41,42). Wastewater surveillance has been proposed as a tool for detecting SARS-CoV-2 on cruise ships, and, if properly scaled, could similarly be adapted for use on individual military vessels, as these vessels share common sewage systems (43). Implementing vessel wastewater surveillance systems would create an established testing system that could provide a sufficient turnaround time to apply necessary measures when early cases are detected.

Vessel design

As with other military and civilian built environments, careful consideration is required when designing and developing said environment to control and prevent exposures to possible and foreseen hazards. Incorporating health and safety considerations is readily applied globally across all industries and aspects of various militaries (e.g., chemicals, radiation), and can be further enhanced for controlling and preventing exposures to biological hazards. As such, through dedicated and intentional measures, the risk of disease transmission may be reduced by purposely designing preventive measures on military vessels to create a sub-optimal environment for transmission. This paradigm has been established by NIOSH and is referred to as Prevention through Design (PtD) (44). While it was originally intended for non-maritime occupational environments, PtD can be tailored and optimized for military vessels. In fact, it has already been recommended for future cruise ship design and development in response to the COVID-19 pandemic (43).

Military vessel design and how it may contribute to human health hazards has been discussed in the published literature as early as 1948 (45). Dr. Ellis discussed several aspects of environmental factors influencing the health of sailors, many of which could have been directly addressed by applying PtD (45). Additionally, during the COVID-19 pandemic, several CDC recommendations for reducing SARS-CoV-2 infection risk were unable to be effectively implemented on military vessels because of the vessel environment (46). These factors included issues with close contact, limitation in certain areas (e.g., dining rooms, berthing, restrooms), and air ventilation, all of which can be addressed on future vessels by applying the PtD paradigm (46).

A major challenge on all maritime vessels, including ones designated for military use, is limited space (46). Such confined quarters can lead to situations in which infectious disease can spread rapidly. The problem is further compounded when treating and isolating infected individuals, an often resource-intensive process on vessels (31). During the COVID-19 pandemic, the U.S. Navy required entire infected crews to quarantine (31). Current U.S. Navy guidance, however, describes quarantine and isolation measures for sailors pre-and post-deployment, but does not outline specific details regarding quarantining on board vessels (39). Another proposed approach to isolation is via "ship zoning", in which vessels are organized into zones based on contamination, interactions, and isolation (15,47,48). While ship zoning may be readily applied to larger vessels (e.g., aircraft carriers), this tactic may not be as feasible on smaller vessels (e.g., destroyers, frigates). Furthermore, it has been suggested to isolate watch teams from each other, so that if an individual within a watch team becomes infected, the entire team can be isolated and replaced together (31). While these approaches to isolation and separation for reducing spread can be impactful, they are still limited by the vessel's finite area and layout. This issue should therefore be accounted for when designing, developing, and building military vessels, as well as during deployment.

Airborne spread of pathogens is a long-established concern, which has become more pronounced during the COVID-19 pandemic. As such, the CDC and other authoritative agencies often recommend using engineering controls, primarily ventilation (49). Inadequate ventilation has been associated with an increased risk of respiratory pathogen transmission, particularly in indoor environments, and there is evidence to support that transmission risk decreases with improved ventilation and airflow (16). Ventilation design and maintenance, however, can be difficult to retrofit in response to bioaerosol exposures. In fact, vessel ventilation systems do not utilize special filtering (31). To incorporate appropriate filtering to aid filtration and reduce bioaerosols would require optimizing and tailoring the ventilation system, which may not be possible across military vessels because of already established requirements and intended uses. Ventilation design and maintenance should therefore be optimized for the possibility of bioaerosols when designing and constructing military vessels.

Vaccines

Historically, vaccines have been an important public health tool for reducing disease transmission, including COVID-19, by limiting the number of susceptible hosts for a pathogen to infect (50,51). Recently, militaries, including the U.S. Department of Navy (DON) and the Australian Defence Force, have mandated COVID-19 vaccinations for active-duty service members (24,52,53). The U.S. DON reported that "vaccination is the most effective tool we have to prevent widespread manifestation of COVID-19 in our force", while also recognizing the other "health protection measures (HPM)" that continue to be effective at reducing COVID-19 transmission, including maintaining a clean work environment, good hygiene practices, and managing workforce exposure (52,53). Nevertheless, beyond COVID-19, other diseases for which vaccines are not available continue to spread in vessel environments, and thus controls such as physical distancing, face masks, and enhanced environment cleaning, could help reduce the risk of transmission. In fact, with regard to COVID-19, the U.S. Navy emphasizes that, "It is always good practice for all crew members to practice HPM whenever practical regardless of vaccination status to help prevent a wide variety of shipborne diseases" (39). Layering vaccinations with other infection control measures creates a more robust approach to infection control, and can be applied not only to SARS-CoV-2, but also many other infectious pathogens.

Collaborative risk assessment-based infection control planning and response

Infection control plans existed for military vessels prior to the COVID-19 pandemic; however, the COVID-19 pandemic highlighted gaps in military infection control response and readiness. Infectious disease prevention requires comprehensive risk assessment, planning, and preparation prior to deploying military personnel (50). In order to develop and execute appropriate risk mitigation strategies, conducting a risk assessment of the hazard first is critical. The assessment's conclusions should then be used to inform control measure decisions, based on the exposure scenario. Following the risk assessment, several frameworks can be applied to select the most effective controls that consider the agent, host, and environment interaction, and establish a comprehensive and flexible infection control plan. Control measures can be applied at each step in the CoI to minimize the risk of transmission from the reservoir host, along the transmission pathway, and at the susceptible host (18). Additionally, the HoC framework establishes categories of controls ordered by increasing effectiveness (i.e., elimination, substitution, engineering controls, administrative controls, PPE), which can be modified to suit the specific hazard, exposure scenario, and environment (54). Using the results of the risk assessment, control measures can be selected according to the HoC to ensure that multiple levels of protective controls are in place at key points in the CoI (18). Layering control measures and optimizing them to the specific circumstances of a vessel's deployment will maximize the reduction in disease transmission and ensure a more effective and robust plan (2,16,19). In fact, the U.S. Navy's Pandemic and Infectious Disease Policy includes a responsibility to perform risk assessment and hazard evaluation to identify where and how workers might be exposed in the workplace, as well as a call to identify measures for limiting infectious disease agent spread in the workplace in line with the principles of HoC (36). Infection control plans must also be flexible enough to accommodate new scientific data and research, which is particularly important for emerging pathogens.

Military vessels that experienced COVID-19 outbreaks, such as the Charles de Gaulle, often experienced a breakdown in communication and information sharing, which underscores the importance of having an established coordinated outbreak response across units (e.g., medical and operational leadership) (13,31). The U.S. Navy's updated Pandemic and Infectious Disease Policy, for example, includes improved coordination methods among various agents as a new responsibility, and suggests that centralizing the overall pandemic or infectious disease management at the Office of the Chief of Naval Operations level may be necessary (36). While coordination within military operations is essential to effectively respond to disease outbreaks and carry out protocols, collaboration between military personnel and experts from health and safety government organizations and agencies, academia, and private industry can foster more comprehensive infection control and risk management plans through shared ideas and expertise. In fact, Chassery and colleagues recommended that militaries systematically consult experts as part of updating pandemic response plans (13). The authors also suggested implementing a fluid exchange of information and skills between different levels of an outbreak management system, including governments, regulatory bodies, and technical and operational management, to improve communication. The CDC's Vessel Sanitation Program, a comprehensive infection control program targeting gastrointestinal pathogen transmission on cruise ships, was developed in cooperation with the cruise ship industry, the U.S. Food and Drug Administration, the international public health community, and the public, and serves as an example of effective collaboration between different stakeholders (55).

Furthermore, infection control response and risk management procedures should be tested in training exercises, to ensure that service members are prepared to effectively execute written plans in the event of an outbreak (31). In a U.S. DOD Inspector General report, in which the Navy's Plans and Response to COVID-19 on Navy Warships and Submarines were evaluated, developing a "plan of action and milestones for Navy Component Commands to conduct biennial Pandemic Influenza and Infectious Disease exercises in accordance with OPNAV Instruction 3500.41A" was recommended (30). The Deputy Chief of Naval Operations agreed with this recommendation, and noted that naval operations would plan and execute a table-top exercise in order to meet the outlined objectives (30). While infection control and risk mitigation plans are important and should be tested in training exercises, military leaders should stay aware, and caution against keeping their commands on high alert all the time. Operating under high alert conditions for sustained periods of time could lead to risk fatigue, which may create issues with baseline compliance of health and safety and infection control protocols and additional implications for personnel readiness. A balance must therefore be reached between implementing useful and necessary controls on military vessels and minimizing risk fatigue by accounting for risk tolerance among service members and military leadership.

Limitations and future research

Several limitations to this assessment should be noted. The review of general military policies and military infection control plans was limited to documents that were publicly available and accessible in the U.S. In addition, because of the nature of national security policies, many military institutions prevent or restrict reporting on COVID-19 infections and deaths, limiting the scope of available data surrounding outbreaks. Additional confidential documents pertaining to infection control on military vessels, therefore, may possibly exist but were inaccessible. The review of the scientific literature was limited to articles available in the English language, which may have limited the perspective on outbreaks observed in other countries and recorded in other languages. Articles relevant to the military, but without vessel- or warship-specific content in the title or abstract were also not included, thus potentially excluding articles that included vessel-specific results in the body of their texts.

The scope of this review was limited to infectious disease transmission and control measures onboard military vessels and did not further consider infection control and risk management strategies prior to deployment, during shore leave, or following deployment completion. The time that crew members spend off the vessel while on duty, however, is an important part of the transmission dynamic, and should be considered in a robust infection control program. The future directions of infection control and risk management onboard vessels proposed in this review is not an exhaustive list. The recommended strategies, which rely on infectious disease epidemiology, ICP, and IH principles, were selected to fill some of the identified gaps in historical military vessel infection control policies. Additionally, according to this review, standardized risk assessment approaches for microbial hazards on military vessels were not previously at the forefront of infection control policy. Because these approaches are critical for understanding how to control hazards, identifying and standardizing these practices in policy and action will allow military organizations to both proactively and actively control infectious outbreaks.

Conclusions

Mitigating pathogen spread on military vessels and other ships is a historical and complex issue because of the shipboard environment and the nature of military operations, such as confined spaces, close and frequent contact between individuals, limited ability to quarantine, and inaccessibility to shore-based assistance. Respiratory pathogen outbreaks have been reported on military vessels, and two notable COVID-19 outbreaks were recorded among American and French nuclear aircraft carriers. Despite the existence of established infection control and risk management plans prior to the COVID-19 pandemic, these protocols were not always fully implemented to help control COVID-19 transmission on vessels. This lack of protocol execution suggests gaps in infection control planning and response onboard military vessels. Several measures that align with infectious disease epidemiology, ICP, and IH principles are proposed, which may help better prepare for and mitigate future COVID-19 outbreaks, as well as outbreaks of other recognized and emerging respiratory pathogens, onboard military vessels. These measures include improved disease monitoring and surveillance by employing more medically-trained crew members and implementing enhanced tools for early detection of cases; optimizing the layout of future vessels via design and zoning; establishing robust vaccination programs for pathogens for which vaccines are available; and developing risk assessment-based, comprehensive, flexible, and multi-layered infection control and risk management plans that incorporate lessons learned from previous disease outbreaks, coordinate with military operational units and outside experts, and are tested through training exercises. Through risk assessment, planning, and proper execution, the risk of COVID-19 and other respiratory pathogen transmissions may be reduced, thereby creating a safer work environment for military vessel crew members, and in turn, protecting national security.

Acknowledgments

The authors would like to thank Carrie Kahn and Tony Cappello for their review, comments, and assistance in preparing this manuscript.
Funding: None.

Footnote

Provenance and Peer Review: This article was commissioned by the Guest Editors (Kenneth A. Mundt and Justine Parker) for the series "Managing COVID-19 Risks in the Workplace" published in *Journal of Public Health and Emergency*. The article has undergone external peer review.

Reporting Checklist: The authors have completed the Narrative Review reporting checklist. Available at https://jphe.amegroups.com/article/view/10.21037/jphe-22-2/rc

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at https://jphe.amegroups.com/article/view/10.21037/jphe-22-2/coif). The series "Managing COVID-19 Risks in the Workplace" was commissioned by the editorial office without any funding or sponsorship. SK is currently employed by Cardno; RKB, KC, HA and CB are currently employed by Cardno ChemRisk, and AS was formerly employed by Cardno ChemRisk. CB has served as a contributor to the AIHA Back to Work Safely Task Force by drafting industry-specific guidance for businesses and consumers to safely reopen after emerging from COVID-19 shelter-in-place/quarantine. The authors have no other conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

References

1. Ho ZJ, Hwang YF, Lee JM. Emerging and re-emerging infectious diseases: challenges and opportunities for militaries. Mil Med Res 2014;1:21.
2. Sanchez JL, Cooper MJ, Myers CA, et al. Respiratory Infections in the U.S. Military: Recent Experience and Control. Clin Microbiol Rev 2015;28:743-800.
3. Malone JD. USS Theodore Roosevelt, COVID-19, and Ships: Lessons Learned. JAMA Netw Open 2020;3:e2022095.
4. Centers for Disease Control and Prevention (CDC). Lesson 1: Introduction to Epidemiology, Section 10: Chain of Infection 2012. Available online: https://www.cdc.gov/csels/dsepd/ss1978/lesson1/section10.html
5. Centers for Disease Control and Prevention (CDC). Lesson 1: Introduction to Epidemiology, Section 8: Concepts of Disease Occurrence 2012. Available online: https://www.cdc.gov/csels/dsepd/ss1978/lesson1/section8.html
6. Sharp TW, Hyams KC, Watts D, et al. Epidemiology of Norwalk virus during an outbreak of acute gastroenteritis aboard a US aircraft carrier. J Med Virol 1995;45:61-7.
7. Bert F, Scaioli G, Gualano MR, et al. Norovirus outbreaks on commercial cruise ships: a systematic review and new targets for the public health agenda. Food Environ Virol 2014;6:67-74.
8. Dill CE, Favata MA. Novel influenza A (H1N1) outbreak on board a US navy vessel. Disaster Med Public Health Prep 2009;3 Suppl 2:S117-20.
9. Khaokham CB, Selent M, Loustalot FV, et al. Seroepidemiologic investigation of an outbreak of pandemic influenza A H1N1 2009 aboard a US Navy

vessel--San Diego, 2009. Influenza Other Respir Viruses 2013;7:791-8.
10. Gupta A, Ray S, Tyagi R, et al. Control of H1N1 influenza outbreak: a study conducted in a naval warship. Journal of Marine Medical Society 2017;19:142.
11. Harwood JL, LaVan JT, Brand GJ 2nd. Two aircraft carriers' perspectives: a comparative of control measures in shipboard H1N1 outbreaks. Disaster Med Public Health Prep 2013;7:29-35.
12. Vera DM, Hora RA, Murillo A, et al. Assessing the impact of public health interventions on the transmission of pandemic H1N1 influenza a virus aboard a Peruvian navy ship. Influenza Other Respir Viruses 2014;8:353-9.
13. Chassery L, Texier G, Pommier De Santi V, et al. A COVID-19 outbreak on board ship: Analysis of the sociotechnical system of epidemiological management in the French Navy. Saf Sci 2021;140:105296.
14. Kasper MR, Geibe JR, Sears CL, et al. An Outbreak of Covid-19 on an Aircraft Carrier. N Engl J Med 2020;383:2417-26.
15. Vicente D, Maves R, Elster E, et al. U.S. Navy's Response to a Shipboard Coronavirus Outbreak: Considerations for a Medical Management Plan at Sea. Mil Med 2021;186:23-6.
16. National Academies of Sciences E, Medicine. Public Health Lessons for Non-Vaccine Influenza Interventions: Looking Past COVID-19. 2021.
17. Palafox NA, Best BR, Hixon A, et al. Viewpoint: Pacific Voyages - Ships - Pacific Communities: A Framework for COVID-19 Prevention and Control. Hawaii J Health Soc Welf 2020;79:120-3.
18. Zisook RE, Monnot A, Parker J, et al. Assessing and managing the risks of COVID-19 in the workplace: Applying industrial hygiene (IH)/occupational and environmental health and safety (OEHS) frameworks. Toxicol Ind Health 2020;36:607-18.
19. Roup B, Kelley PW. Principles of infection control and prevention during military deployment. Washington, DC: Borden Institute, 2005.
20. U.S. Department of Defense (DoD). Instruction 6200.03: Public Health Emergency Management (PHEM) within the DoD. March 28, 2019.
21. Chief of Naval Operations. OPNAV Instruction 3500.41A. In: U.S. Department of the Navy, editor. November 19, 2018.
22. Chief of Bureau of Medicine and Surgery. BUMED Instruction 6220.9B. In: Department of the Navy, editor. April 14, 2011.
23. U.S. Department of the Navy. Return to the Workplace: COVID-19 Guidance and Resources. July 28, 2020.
24. Australian Government - Department of Defence. COVID-19 Taskforce n.d. Available online: https://www.defence.gov.au/about/taskforces/covid-19-taskforce
25. Centers for Disease Control and Prevention (CDC). COVID-19 PubMed Search Alert 2020. Available online: https://www.cdc.gov/library/researchguides/2019novelcoronavirus/pubmedsearchalert.html
26. Chief of Naval Operations. M-5100.23: Navy Safety and Occupational Health Manual In: Department of the Navy, editor. June 5, 2020.
27. U.S. Department of Defense (DoD). Directive 6200.04. October 9, 2004.
28. Bylicki O, Paleiron N, Janvier F. An Outbreak of Covid-19 on an Aircraft Carrier. N Engl J Med 2021;384:976.
29. Alvarado GR, Pierson BC, Teemer ES, et al. Symptom Characterization and Outcomes of Sailors in Isolation After a COVID-19 Outbreak on a US Aircraft Carrier. JAMA Netw Open 2020;3:e2020981.
30. Inspector General. Evaluation of the Navy's Plans and Response to the Coronavirus Disease-2019 Onboard Navy Warships and Submarines (DODIG-2021-049). In: Department of Defense (DoD), editor. February 4, 2021.
31. Martin B, Brahmbhatt T. Readiness Implications of Coronavirus Infections on US Navy Ships. Rand Corp Santa Monica CA; 2021.
32. U.S. Department of the Navy. US Navy COVID-19 Prevention Framework. April 13, 2020.
33. U.S. Department of the Navy. US Navy COVID-19 Mitigation Framework Protect the Force and Preserve War Fighting Readiness. April 23, 2020.
34. U.S. Department of the Navy. US Navy COVID-19 Recovery Framework Recover the Force and Restore War Fighting Readiness. April 15, 2020.
35. U.S. Department of the Navy. US Navy COVID-19 Standardized Pre-Deployment Guidance Clean Crew, Ready for Mission. April 22, 2020.
36. Chief of Naval Operations. OPNAV Instruction 3500.41B. In: U.S. Department of the Navy, editor. July 12, 2021.
37. U.S. Navy COVID-19 Updates 2020. Available online: https://web.archive.org/web/20200519124614/https://navylive.dodlive.mil/2020/03/15/u-s-navy-covid-19-updates/
38. U.S. Marine Corps. COVID-19 Coronavirus 2022. Available online: https://www.marines.mil/Coronavirus/
39. U.S. Department of the Navy. NAV21110: U.S. Navy COVID-19 Standing Guidance Update 1. 2021.

40. Kirby AE, Walters MS, Jennings WC, et al. Using Wastewater Surveillance Data to Support the COVID-19 Response - United States, 2020-2021. MMWR Morb Mortal Wkly Rep 2021;70:1242-4.
41. Betancourt WQ, Schmitz BW, Innes GK, et al. COVID-19 containment on a college campus via wastewater-based epidemiology, targeted clinical testing and an intervention. Sci Total Environ 2021;779:146408.
42. Karthikeyan S, Nguyen A, McDonald D, et al. Rapid, Large-Scale Wastewater Surveillance and Automated Reporting System Enable Early Detection of Nearly 85% of COVID-19 Cases on a University Campus. mSystems 2021;6:e0079321.
43. Brewster RK, Sundermann A, Boles C. Lessons learned for COVID-19 in the cruise ship industry. Toxicol Ind Health 2020;36:728-35.
44. The National Institute for Occupational Safety and Health (NIOSH). Prevention through Design 2013. Available online: https://www.cdc.gov/niosh/topics/ptd/default.html
45. Ellis FP. Health and Efficiency in Warships. British Medical Journal 1948;1:587.
46. Dutton LK, Rhee PC, Shin AY, et al. Combating an invisible enemy: the American military response to global pandemics. Mil Med Res 2021;8:8.
47. Kordsmeyer AC, Mojtahedzadeh N, Heidrich J, et al. Systematic Review on Outbreaks of SARS-CoV-2 on Cruise, Navy and Cargo Ships. Int J Environ Res Public Health 2021;18:5195.
48. World Health Organization (WHO). Handbook for Management of Public Health Events on Board Ships. In: International Health Regulations, editor. 2016.
49. Centers for Disease Control and Prevention (CDC). Ventilation in Buildings 2021. Available online: https://www.cdc.gov/coronavirus/2019-ncov/community/ventilation.html
50. Michel R, Demoncheaux JP, Créach MA, et al. Prevention of infectious diseases during military deployments: a review of the French armed forces strategy. Travel Med Infect Dis 2014;12:330-40.
51. Mura M, Haus-Cheymol R, Tournier JN. Immunization on the French Armed Forces: Impact, organization, limits and perspectives. Infect Dis Now 2021;51:583-9.
52. U.S. Department of the Navy. ALN21062: 2021-2022 Department of Navy Mandatory COVID-19 Vaccination Policy. 2021.
53. U.S. Department of the Navy. NAV21190: 2021-2022 Navy Mandatory COVID-19 Vaccination and Reporting Policy. 2021.
54. The National Institute for Occupational Safety and Health (NIOSH). Hierarchy of Controls 2015. Available online: https://www.cdc.gov/niosh/topics/hierarchy/default.html
55. U.S. Department of Health and Human Services, Centers for Disease Control and Prevention (CDC), U.S. Public Health Service. Vessel Sanitation Program 2018 Operations Manual. 2018.

doi: 10.21037/jphe-22-2
Cite this article as: Brewster RK, Chan K, Allen H, Sundermann A, Keane S, Boles C. Future directions of infection control and risk management on military vessels: a narrative review. J Public Health Emerg 2022;6:33.

